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DESIGN PROCEDURES FOR DISSOLVED OXYGEN CONTROL OF ACTIVATED SLUDGE PROCESSES

Municipal Environmental Research Laboratory
Office of Research and Development
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DESIGN PROCEDURES FOR DISSOLVED OXYGEN CONTROL OF ACTIVATED SLUDGE PROCESSES

by

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is the necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The purpose of this manual is to provide a recommended design procedure to guide the design engineer in the selection of aeration equipment and control techniques for achieving optimal dissolved oxgen control of the activated sludge process.

Francis T. Mayo, Director
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ABSTRACT

This report presents design procedures and guidelines for the selection of aeration equipment and dissolved oxygen (DO) control systems for activated sludge treatment plants. A review of process configurations and design parameters is made to establish system requirements. Aeration methods, equipment and application techniques are examined and selection procedures offered. Various DO control systems are described with recommendations for system applications to various aeration equipment types and process configurations. Performance, operational and maintenance data for aeration equipment and DO control systems for twelve activated sludge plants is presented. This information and other design recommendations in the report are used to develop automatic DO control systems for various size hypothetical activated sludge system configurations for an economic analysis of manual and automatic DO control. The conclusion is drawn that the capital and operating costs of automatic DO control systems are justified for activated sludge plants larger than 1 mgd (44 dm^3/s) provided equipment is selected and applied in accordance with the guidelines of the design manual and a power cost equal to or greater than the national average power rate is applicable.

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FIGURES (cont'd)

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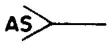
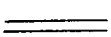
LIST OF ABBREVIATIONS AND SYMBOLS[a]

Instrument Identification Letters

AC	analysis controller
AE	analysis element
AIC	analysis indicating controller
AIR	analysis indicating recorder
AIT	analysis indicating transmitter
AR	analysis recorder
AS	analysis switch
AY	analysis computing relay
FE	flow element
FI	flow indicator
FIC	flow indicating controller
FT	flow transmitter
HIK	manual control action
HS	manual (hand) switch
KC	time (step) controller
PIC	pressure indicating controller
PIT	pressure indicating transmitter
TR	temperature recorder
TT	temperature transmitter
UC	multivariable controller
UY	multivariable computing relay
ZIC	position indicating controller
ZT	position transmitter
ZY	position computing relay

Instrument Line Symbols

	process flow line
	pneumatic signal
	electrical signal
	air supply
	mechanical linkage

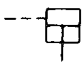
Instrument Symbols

	local mounted instrument
	rear panel instrument
	front panel instrument
	interlock

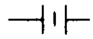
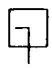
<u>Control Valve Body Symbols</u>

	gate valve
	globe valve
	plug valve
	ball valve
	butterfly valve
	check valve
	3-way valve
	4-way valve

<u>Control Valve Actuator Symbols</u>

	spring opposed diaphragm
	pilot actuated cylinder
	hand actuator
Ⓜ	rotary motor

<u>Primary Sensing Element Symbols</u>

	orifice plate
	venturi or flow tube
	pitot tube

<u>Relay and Controller Function Designations</u>

I-O	on-off control
Σ	add or totalize
Δ	subtract
Δ I-O	differential gap control
$\pm$, +, -	bias
%	proportional control
$\boxed{\times}$	multiply
$\boxed{\div}$	divide
$\boxed{\sqrt{}}$	extract square root
x^n	raise to power
f (x)	characterize
$\boxed{>}$	high select
$\boxed{<}$	low select
I/P	current to pneumatic
P/I	pneumatic to current
$\int$	integral control
d/dt	derivative control

Other Abbreviations and Symbols

AA	aeration air	SP	set point
C_xH_x	hydrocarbons	S	starter
DO	dissolved oxygen	TOC	total organic carbon
FC	fail closed	T	trap
FO	fail open	VS	variable speed drive
LEL	lower explosive limit		panel patchboard
O_2	oxygen		field patchboard

[a]Extracted from Instrument Society of America "Instrument Symbols and Identification," (ISA-S5.1-1973 or ANSI Y32.20-1975) (13). Any abbreviations and symbols used in this manual and not listed here can be found in Reference 13.

UNITS

The International System of Units (SI) is used in this manual in accordance with American Society of Testing Materials (ASTM) Metric Practice Guide E 380-72 or American National Standards Institute (ANSI) Z 210.1-1973.

ACKNOWLEDGMENTS

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Sincere thanks is offered to the management and operating staffs of the treatment plants at which performance tests were run for the purposes of this report or from which data was obtained from past testing. Particular thanks and appreciation goes to the following:

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SECTION 1

INTRODUCTION

Control of air or pure oxygen dissolution in the mixed liquor is an important parameter in the activated sludge process. Increasingly, there is an economic incentive to minimize unnecessary oxygenation. The hypothesis is that a desirable automatic control strategy is to add only sufficient air or oxygen to meet the time-varying demand of the mixed liquor. Field tests indicate that the benefits of such a control strategy are improved process performance and efficiency.

The purpose of this manual is to provide a recommended design procedure to guide the design engineer in the selection of aeration equipment and control techniques for achieving optimal dissolved oxygen control of the activated sludge process. The information included herein on performance, operation and maintenance of various dissolved oxygen control systems, instrumentation and mechanical equipment details, and associated capital and operating costs was obtained from the available literature, reports from operating plants, progress reports of demonstration studies, and private communications with investigators actively working in the field. Design guidelines are developed from these sources.

SECTION 2

CONCLUSIONS

The capital and operating cost of automatic dissolved oxygen (DO) control systems is justified for activated sludge plants larger than 44 dm^3/s (1 mgd), provided equipment is selected and applied in accordance with the guidelines of this manual and a power rate equal to or greater than the national average power rate is applicable.

Automatic DO control may not be warranted in plants with (a) constant loading conditions (b) insufficient oxidation tank or aerator capacity or (c) aerator turndown limitations.

Careful attention should be given to blower selection by the designer if power savings are to be expected using an automatic DO control system.

If aeration blowers are used to supply air to two or more separate processes, the control systems which regulate air supply to meet the varying air demands of each process should be decoupled to prevent interaction under dynamic operating conditions.

DO probe layouts should be flexible enough to permit reconfiguration while the plant is on line. Multiple DO probe receptacles should be provided in each tank to permit probe relocation.

An effective method of activated sludge DO control with centrifugal blowers is a combination of a discharge pressure control loop for the blowers and a DO regulated flow control loop for each oxidation tank air feed header.

Centrifugal and axial blowers have operating characteristics that allow horsepower to be conserved over a variable flow range and are, therefore, better suited to automatic DO control systems than positive displacement blowers or mechanical mixers.

DO probe maintenance is a major expense in automatic DO control systems. Maintenance time can be significantly reduced through proper probe selection, good maintenance programs and probe installations that facilitate probe access for cleaning and calibration.

Automatic DO control offers the potential advantage of decreased effluent quality variability through optimization of the air/oxygen application rate.

Managers of existing activated sludge plants should examine the performance of their existing DO control systems in terms of effluent quality and operation and maintenance costs. Where improvement is possible, modifications to, or substitution of, the control system in accordance with guidelines presented herein should be considered. Projected benefits should be compared to net annual costs of new equipment, where such comparisons can be estimated.

Managers of existing plants with automatic control systems should run long term performance tests of manual compared to automatic DO control to ascertain how effectively their existing control systems perform. Modifications to the control system should be considered if results are less than expected.

Designers of activated sludge plants should consider potential power savings through automatic DO control when selecting aeration equipment. The performance record of various DO control systems should be examined to determine which system is desirable for a particular plant configuration. Automatic DO control should be considered at the onset, rather than as an afterthought, of design.

SECTION 3

RECOMMENDATIONS FOR FUTURE RESEARCH

An important by-product of this study is the identification of certain areas in the application of dissolved oxygen control systems that warrant further research. The itemization below is not exhaustive but does reference many specific problems observed in the field. Research areas are identified in terms of application of DO control to the activated sludge process.

1. Evaluate the effect of dissolved oxygen control system set point level on effluent quality and sludge handling.
2. Determine the optimum dissolved oxygen set point, considering both performance and economics, for various process configurations.
3. Develop guidelines for location of DO probes in oxidation tanks for different process configurations, such as conventional, step feed, extended aeration and contact stabilization.
4. Evaluate different control strategies employing DO measurement and control such as feedforward, feedback, adaptive and optimal control.
5. Recommend maintenance procedures and equipment installation guidelines for efficient maintenance of DO probes.
6. Evaluate different methods of conserving power when applying mechanical aeration and positive displacement blowers in automatic DO control systems.
7. Identify wastewater characteristics that lead to greater frequency of DO probe cleaning.
8. Evaluate use of cleaner/agitator assemblies compared to careful placement of DO probes in oxidation tanks in terms of resultant probe maintenance requirements and accurate DO readings.
9. Evaluate the capital cost, operating cost, and performance of other devices compared to DO probes for measuring oxygen demand in oxidation tanks.
10. Evaluate current DO probe design technology for activated sludge DO control system application. Rank desirable DO probe characteristics in order of priorities.
11. Conduct additional longer term tests of automatic vs manual DO control of the activated sludge process at a large number of plants. Evaluate any resultant power savings and process performance improvements in terms of possible correlation with specific DO control systems, plant design or operating characteristics.

SECTION 4

UNIT PROCESSES

The activated sludge process has evolved through the years into a versatile biological treatment method. It has been adapted to a variety of biological waste treatment problems, resulting in several modifications to the basic method. This chapter describes preaeration and postaeration systems and schematics and process dynamics of various activated sludge systems.

PREAERATION SYSTEMS

Aeration of wastewater prior to primary sedimentation has been practiced for over 50 years in the United States. It is generally employed for odor control and to improve treatability of wastewater. Short aeration periods of 15 minutes or less are adequate for these purposes, although longer aeration periods yield the additional benefits of grease separation and improved solids flocculation (28, 31). Additionally, aeration-induced agitation improves separation of organic and inorganic fractions of the solids, which enhances grit removal and promotes uniform distribution of suspended solids to the treatment works.

The two basic parameters in preaeration system design are air feed rate and detention time. Preaeration tank depths are generally about 4.5 m (15 feet) , and air requirements range from 0.75-3 m^3/m^3 (0.1 to 0.4 cu ft per gal) of wastewater (20). In order to maintain proper agitation, the air supply system should be capable of providing air at the rate of 0.5-1.9 dm^3/s (1.0 to 4.0 cfm) in the wastewater distribution channel per lineal 0.3 m (foot) of channel.

Where chemical addition is combined with the preaeration process, air requirements may vary from those reported for conventional preaeration systems. Studies at the Central Contra Costa Sanitary District in Concord, California have shown that air supply rates for lime flocculation may be lower than the rates used for conventional preaeration to avoid shearing of floc (12, 15). Effective preaeration has been achieved with detention times of 45 minutes and less.

POSTAERATION SYSTEMS

Minimum effluent dissolved oxygen (DO) concentrations are required for treatment plants in many states to minimize oxygen depletion of receiving waters. Minimum DO concentrations of 4 to 5 ppm are common criteria for surface water quality. Yet DO levels in secondary effluents normally range from 0.5 to 2.0 ppm. Postaeration is a way of increasing effluent dissolved oxygen to meet discharge requirements.

There are four possible methods of postaerating treatment plant effluent. Two of these methods, diffused aeration and mechanical aeration, are essentially the same as those employed in biological treatment processes. The other methods, called cascade aeration and U-tube aeration, can be attractive alternatives. In cascade aeration, effluent is discharged over a series of steps or weirs in thin layers with the objective of maximizing turbulence, thereby increasing oxygen transfer. Cascade aeration is an attractive postaeration technique where sufficient head is available after secondary clarification. While U-tube aerators have not yet been employed in postaeration, they have been suggested as an attractive alternative to other postaeration methods (31).

ACTIVATED SLUDGE SYSTEMS

In the activated sludge process, suspensions of microorganisms stabilize soluble and colloidal organics to carbon dioxide and water in the presence of molecular oxygen. In the stabilization process, waste organic material is used to synthesize new cells, some of which subsequently undergo endogenous respiration as substrate concentration decreases. Synthesized cells are removed from treated wastewater in secondary clarifiers. For continuous operation, a major fraction of the cells must be recycled to the oxidation tank. Excess sludge is withdrawn from the clarifier underflow for disposal. Oxygen is required in the process to support oxidation and synthesis reactions.

Due to the adaptability of the process, activated sludge plants have been designed with a variety of flow plans. Nearly all these modifications have been outgrowths of the conventional process flow plan and have resulted from attempts to improve or correct deficiencies in the conventional system. There are advantages and disadvantages to each modification. Some achieve better biochemical oxygen demand (BOD) and suspended solids (SS) removals than others. Some cost less to construct; others cost less to operate. Some produce less sludge, and some provide better waste removal. Each of these factors must be considered in selecting a flow plan for a particular application.

Conventional Process

The conventional activated sludge process is shown schematically in Figure 1. In this system, primary effluent is mixed with return activated sludge and passed on to the oxidation tank as mixed liquor. The oxidation tank is the biochemical reactor in which microorganisms in the mixed liquor aerobically stabilize organics in the wastewater. Mixed liquor leaving the oxidation tank is displaced into secondary clarifiers, where suspended solids are separated from treated wastewater. A large fraction of the settled biomass is returned to the head of the oxidation tank as returned activated sludge to sustain the continuing reaction. Excess solids are removed from the system as waste activated sludge. Clarified secondary effluent continues through the plant for subsequent treatment and disposal.

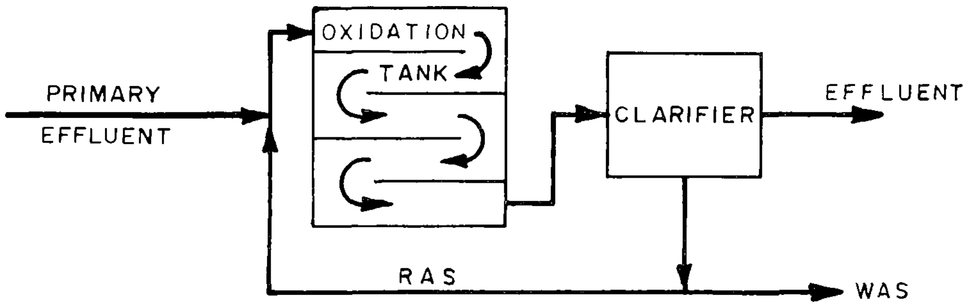


Figure 1. Conventional activated sludge process.

Most conventional activated sludge systems are designed for organic loadings of 2.3-5.8 mg/s/kg MLVSS (0.2 to 0.5 lbs BOD/day/lb MLVSS). Designs are usually based on volumetric loadings of 3.7-7.4 mg BOD/m^3/s (20 to 40 lbs BOD/day/1000 cu ft) and sludge retention times of 5 to 15 days. Oxidation tanks commonly provide 6 to 10 hours of aeration time. Sludge return rate is normally between 25 and 50 percent with minimum and maximum rates of 15 and 75 percent respectively.

To achieve plug flow, oxidation tanks are designed as long rectangular basins with length to width ratios ranging from 5:1 to 50:1. Primary effluent and return activated sludge are fed at one end of the tank and treated mixed liquor is withdrawn at the opposite end. In addition to supplying oxygen for stabilization, aeration mixes the tank contents. Conventional air diffusion equipment is arranged to obtain a "spiral-flow" action perpendicular to the direction of waste flow.

A disadvantage of the conventional system is that plug flow produces a continually changing environment within the oxidation tank. The concentration of substrate continually decreases as the flow proceeds down the tank. Consequently, food/microorganism (F/M) ratio is constantly varying, with higher BOD loadings at the head of the oxidation tank and relatively low loadings at the effluent end. Since air is supplied evenly throughout the tank, DO concentrations at the head of the tank are low, while those at the effluent end are much higher.

The conventional plant can be modified to incorporate a tapered aeration system. With tapered aeration, the air supply system is "tapered" to match actual oxygen demand in the oxidation tank. More oxygen is supplied at the front of the tank, where oxygen demand is greatest, decreasing in proportion to load toward the discharge end of the tank. A well designed tapered aeration system should have a fairly constant oxygen level throughout the oxidation tank. In order to balance aeration taper against actual oxygen load, it is necessary to accurately determine the relationship between oxygen demand and longitudinal distance along the tank. Figure 2 shows an average relationship for plug flow systems. Such a curve can be useful for estimating aeration taper requirements.

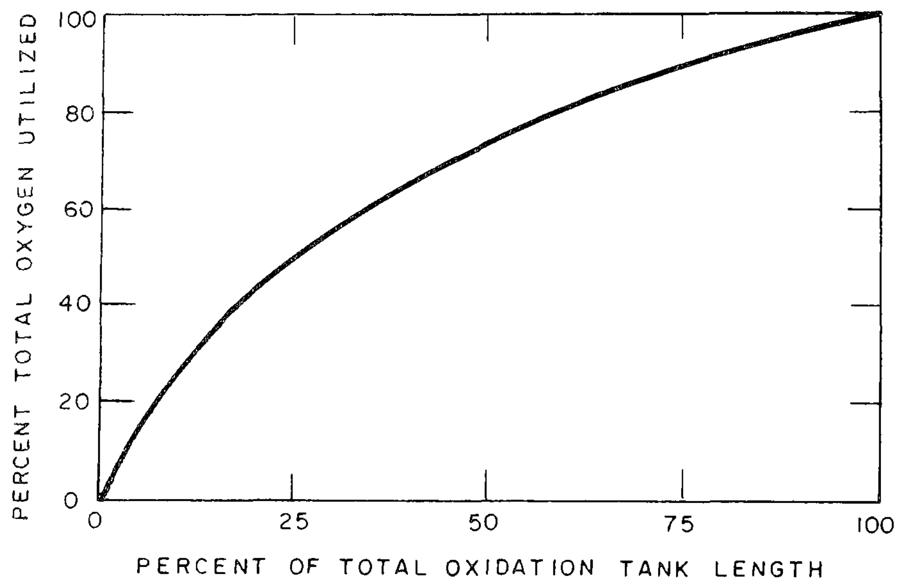


Figure 2. Oxygen Utilization in a plug flow system.

Volumetric loading and food to microorganism ratios for tapered aeration plants are in the same range as those used in conventional activated sludge systems. Oxygen requirements average about 1.4 mg/s/g MLVSS (5 mg/l/hr/1000 mg MLVSS) and detention time varies from one to 12 hours (17).

Complete Mix Process

In the complete mix activated sludge process, effluent wastewater and return activated sludge are introduced uniformly throughout the oxidation tank, as shown in Figure 3. This uniform load distribution results in a constant oxygen demand throughout the tank and in a more homogeneous sludge community. As a result, the oxidation tank volume in a complete mix system is used more efficiently than in a conventional plant, permitting design for higher volumetric loadings. Complete mix plants have been designed for volumetric loadings of 9.3-22 mg BOD/m^3/s (50 to 120 lb BOD/day/1000 cu ft) at F/M ratios of 2.3-6.9 mg BOD/s/kg MLVSS (0.2 to 0.6 lb BOD/day/lb MLVSS) and hydraulic detention times of 3 to 5 hours (20). For this type of system, return sludge ratios should be as high as possible, consistent with good pumping economics. The recommended range for recycle ratios is 35 to 100 percent (17).

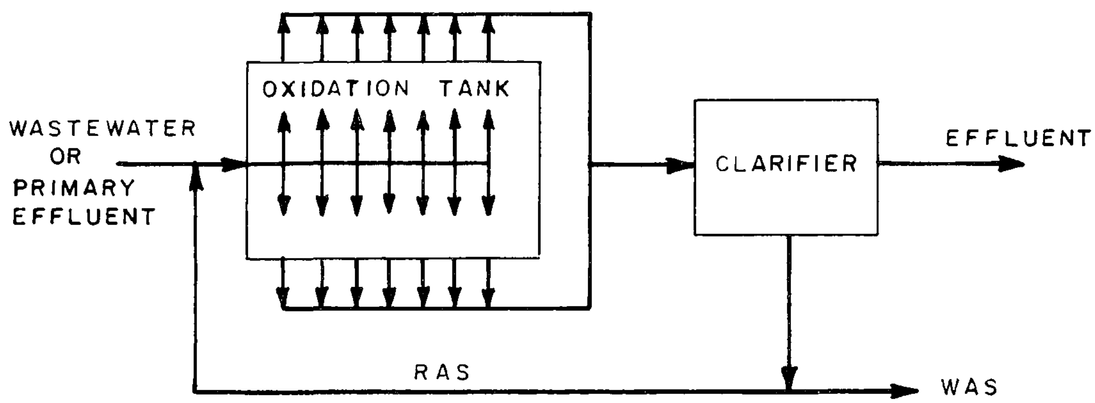


Figure 3. Complete mix process.

In the complete mix system, influent wastewater and return sludge should be mixed with the entire tank contents almost instantaneously. This is achieved through both proper initial flow distribution and adequate mixing in the tank. For rectangular tanks, influent distribution and mixed liquor withdrawal normally occur along the entire longitudinal tank axis, as shown in Figure 3. Aeration is normally arranged to mix contents in the longitudinal direction. This provides greater dispersal of the influent and more rapid mixing within the tank. A round or square aeration tank is more desirable where mechanical aerators are to be used. Depending on the size and arrangement of mechanical aerators, single or multiple point feed and discharge can be provided. Mechanical aerators are especially attractive for use in complete mix systems because they (a) put more energy into the mixing process, and (b) mix in all directions (17).

As shown in Figure 4, complete mixing permits use of higher BOD loadings for a given temperature and oxygen uptake rate. Lesperance (17) has noted that this increased BOD loading is only an apparent increase. In the complete-mix system, more of the microorganisms in the mixed liquor are actively stabilizing waste organics due to process homogeneity. Therefore, while the biochemical reaction rate does not increase, a higher effective BOD loading rate results.

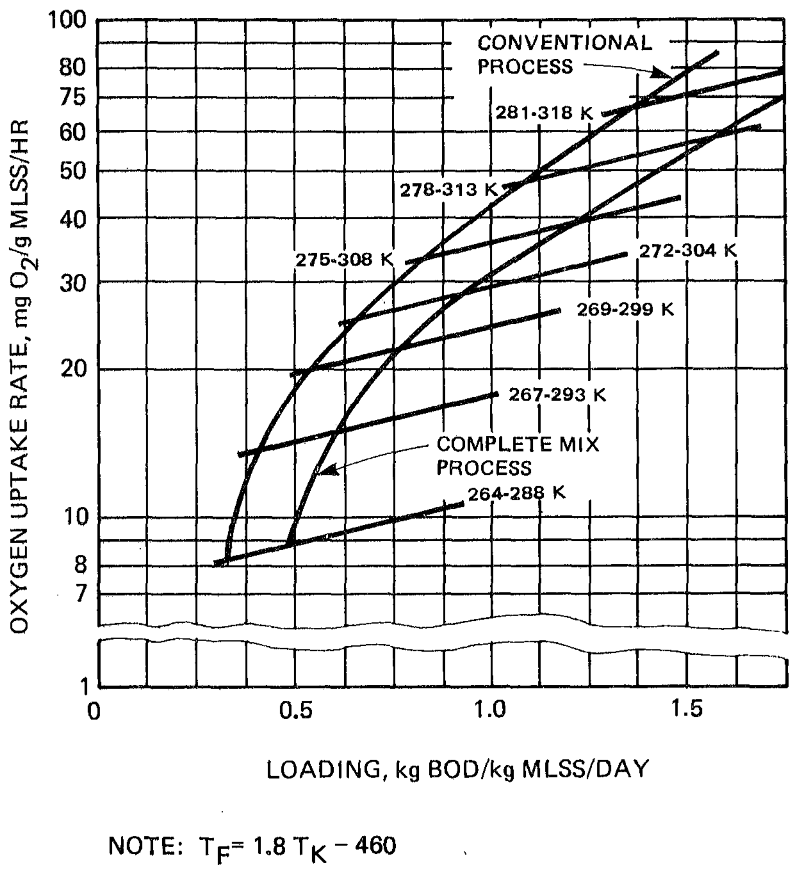


Figure 4. Oxygen utilization in activated sludge systems.

Figure 4 was compiled from full scale and pilot plant operating data on oxygen uptake rates for a variety of wastes, including sewage, oil refinery pharmaceutical, chemical, and pulp and paper plant wastes (17). This figure is intended to show only an operating range for activated sludge processes. Actual plant performance depends upon the capability and characteristics of process components, such as oxidation tanks and aeration equipment. Furthermore, Figure 4 does not account for diurnal flow and load variations, which can increase oxygen uptake rate 40 to 60 percent above the average daily design figure for carbonaceous oxidation alone.

Step Feed Process

A typical flow diagram for a step feed activated sludge plant is shown in Figure 5. The influent wastewater is split into several portions, which are introduced at several points along the oxidation tank. Return sludge is normally introduced at the head of the oxidation tank. Distribution of influent flow along the oxidation tank compensates for the high initial oxygen demand normally experienced in conventional plants.

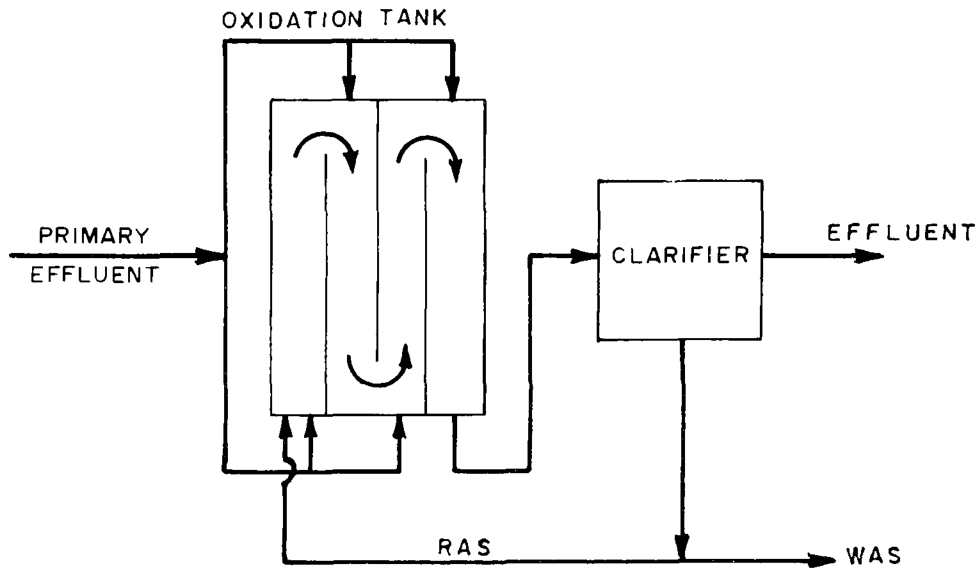


Figure 5. Step feed process.

As in the conventional activated sludge system, air is fed uniformly along the tank. As a result of step feeding, however, a plot of dissolved oxygen versus tank length results in a characteristic saw-tooth curve, which has given rise to the misnomer "step aeration". Regardless of name, the net result is that partial load equalization produces a more homogeneous system. Hence, the process can take higher BOD loadings with shorter detention times and more effective utilization of air.

Step feed plants are usually designed for volumetric loadings of 7.4-11 mg BOD/s/m^3 (40 to 60 lb BOD/day/1000 cu ft) and F/M ratios of 2.3-4.6 mg BOD/s/kg MLVSS (0.2 to 0.4 lb BOD/day/lb MLVSS). Plant detention times are characteristically three to five hours and efficiencies range from 85 to 95 percent BOD removal.

Sludge Reaeration Process

The sludge reaeration process is a variation of the step feed process. It is a technique for improving systems which are not achieving design BOD reduction efficiency due to insufficient oxidation tank volume. In general, the size of a step aeration tank with sludge reaeration can be less than half the size of a conventional tank when both tanks receive the same influent solids loading (2).

Sludge reaeration can be provided before or after secondary clarification. In some cases, sludge reaeration is provided in an activated sludge system by eliminating wastewater feed to the first pass and directing the flow to the downstream passes. A sludge reaeration zone is thereby established in the first pass (4).

Contact Stabilization Process

As shown in Figure 6, the contact stabilization process is essentially a two-step activated sludge process. In the first step, wastewater BOD in the colloidal or insoluble state is rapidly removed from wastewater in a relatively short contact time by the combined mechanism of biological sorption, synthesis, and flocculation. For domestic wastes, this process proceeds rapidly, requiring as little as 20 to 40 minutes for removal of most of the colloidal, finely suspended and dissolved organics. However, while the BOD is almost completely adsorbed, or physically removed from the liquid in this time, the microorganisms in the sludge have not had enough time to reduce or stabilize the organic matter. In the second stage of the process, settled sludge is pumped to a stabilization tank where microorganisms are aerated in the absence of a food supply, metabolically assimilating adsorbed organics. Microorganisms are retained in the stabilization tank until they enter endogenous respiration, becoming "lean and hungry". Thus, when they are finally discharged to the contact tank, they are capable of rapidly removing large amounts of BOD.

The contact stabilization process is designed for volumetric loadings of 11-14 mg BOD/s/m^3 (60 to 75 lb BOD/day/1000 cu ft) with F/M ratios of 2.3-6.9 mg BOD/s/kg MLVSS (0.2 to 0.6 lb BOD/day/lb MLVSS). This process is commonly thought to have a somewhat lower BOD removal efficiency than the conventional or complete-mix processes. However, efficiencies of 90 to 94 percent have been reported for a number of plants in Texas and New Jersey (31). For domestic wastewater containing normal amounts of insoluble, colloidal BOD, contact tanks are designed for detention times of 0.5 to 1 hour at average flow, and stabilization tanks are designed for 3 to 6 hours based on sludge recycle flow. Total air required for this process is similar to that for conventional activated sludge. Normally, an equal amount of air is required for the contact and reaeration tanks.

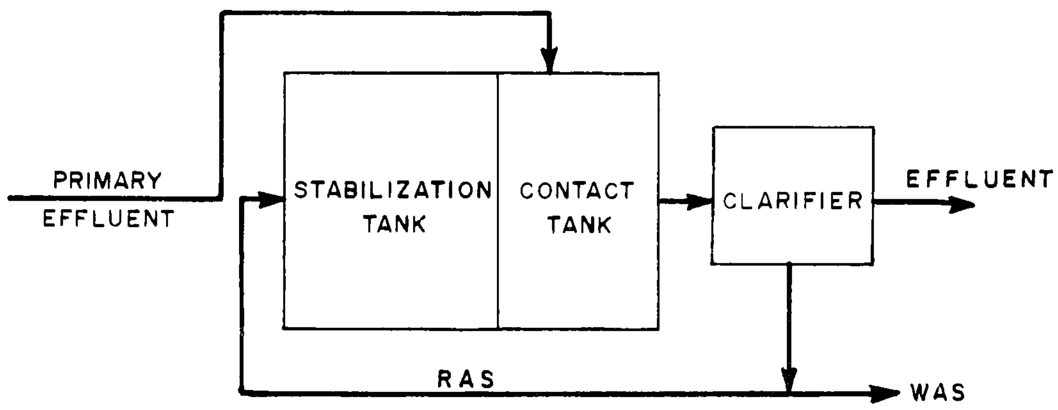


Figure 6. Contact stabilization process.

The major advantage of the contact stabilization process is the reduced oxidation tank volume needed to support the biochemical reaction. However, this advantage is lost where BOD is largely in the soluble state, as in the case of many industrial wastes. In addition to a smaller total requirement for aeration volume, the contact stabilization process has the advantage of being able to sustain greater shock and toxic loadings than the conventional process. This resistance to upset is largely due to the biological buffering capacity of the stabilization tank and to isolation of most of the activated sludge from the main plant flow stream.

Hatfield and Kraus Processes

Some types of wastes, especially fruit and cannery wastes, are deficient in nitrogen, an essential nutrient for microorganism growth. Uncorrected, this deficiency limits waste treatability. The Hatfield and Kraus processes are variations of the contact stabilization process in which anaerobic digester effluent is supplied to the sludge reaeration unit. This fortifies the largely carbonaceous activated sludge solids with amino acids and other nitrogenous byproducts of the anaerobic digestion process. As shown in Figure 7, the essential difference between the Hatfield and Kraus processes is that in the Kraus process some return sludge bypasses the reaeration unit and goes directly to the mixed liquor oxidation tank.

These processes are normally designed on the basis of volumetric loadings of 7.4-18 mg BOD/s/m^3 (40 to 100 lb BOD/day/1000 cu ft) and F/M ratios of 3.5-9.2 mg BOD/s/kg MLVSS (0.3 to 0.8 lb BOD/day/lb MLVSS) with hydraulic detention times of 4 to 8 hours (20).

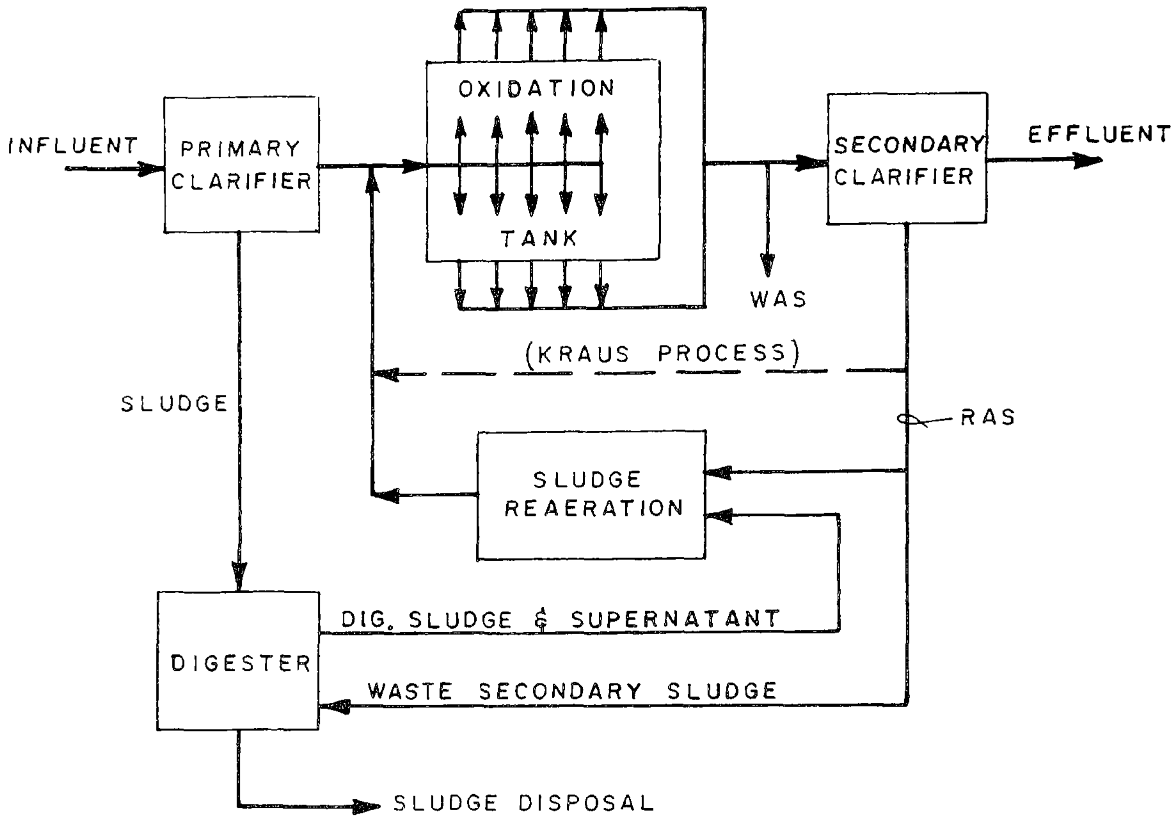


Figure 7. Hatfield and Kraus processes.

Short-Term Aeration Process

The short-term aeration process is also known as high rate aeration and modified aeration. As the names imply, the process is a modification of the conventional activated sludge system which applies high loading rates with short aeration times. The major advantage of the process is construction economy due to the reduced oxidation tank capacities required. However, due to the relatively small mass of microorganisms in contact with the wastewater and the short period of contact, a greater amount of unused BOD remains in the process effluent. Additionally, the process employs high F/M ratios. Net growth of volatile suspended solids is relatively large in these systems. Incomplete removal of these solids degrades effluent quality; complete removal presents a problem of sludge disposal.

The short-term aeration process follows the same basic schematic as the conventional activated sludge process. However, the short-term process allows volumetric loadings of 18-46 mg BOD/s/m^3 (100 to 250 lb BOD/day/1000 cu ft) and F/M ratios of 5.8-60 mg BOD/s/kg MLVSS (0.5 to 5 lb BOD/day/lb MLVSS) (38). Hydraulic detention times are normally in the range of 0.5 to 2 hours, and the process is reported to have an efficiency of 75 to 90 percent BOD removal (20).

Extended Aeration Process

The extended aeration process follows the same basic schematic as the conventional activated sludge process. By virtue of its low loadings and long aeration times, the extended aeration process operates in the endogenous respiration portion of the growth curve.

As originally conceived, the extended aeration process was designed to provide continuous sludge return with no sludge wastage. In practice, this meant that the net growth of suspended solids was wasted from the system in the process effluent. As a result, normal domestic flows treated by the extended aeration process have shown apparent BOD removals of only 75 to 85 percent. However, Lesperance (17) reports that with competent daily operating control and proper sludge control and wastage, extended aeration systems should yield a BOD reduction of 98 percent or better.

With the exception of comminution of solids, primary treatment is normally omitted from the extended aeration flow sheet. Treatment plants are generally sized for less than 44 dm^3/s (1 mgd) capacity, with wastes entering the plant continuously or intermittently. Plants are designed for volumetric loadings of 1.8-4.6 mg BOD/s/m^3 (10 to 25 lb BOD/day/1000 cu ft) and F/M ratios of 0.58-1.7 mg BOD/s/kg MLVSS (0.05 to 0.15 lb BOD/day/lb MLVSS). Hydraulic detention times are normally in the range of 18 to 36 hours and mean cell residence times range from 20 to 30 days.

SECTION 5

AERATION SYSTEMS

The environmental engineer designing a system which employs aeration is confronted with a bewildering assortment of aeration equipment and proprietary devices, all purporting to provide the most economical solution to his design problem. Based on his assessment of economic and functional considerations, he must select an aeration method and choose the applicable aeration device. This chapter reviews aeration methods, aeration equipment, and basic considerations in aeration systems design.

OXYGEN TRANSFER

Aeration devices are used for many purposes in wastewater treatment, including preaeration, postaeration, grit removal, channel aeration, pond aeration and activated sludge aeration. The comments in this chapter are directed primarily to aeration of mixed liquor in the activated sludge treatment process. In that context, aeration has four basic functions, which are: (a) providing oxygen for biological oxidation of organic substrates and respiration of the microorganisms in the oxidation tank, (b) agitating the mixed liquor to prevent sludge from settling in the oxidation tank, (c) mixing to ensure intimate contact between activated sludge microorganisms and waste organic matter in the mixed liquor, and (d) removing carbon dioxide produced in the oxidation of carbonaceous and nitrogenous substances.

Oxygen Transfer Theory

Gas transfer basically involves exchange of molecules between gases and liquids. All that is required for exchange to occur is a gas-liquid interface with a disequilibrium in the concentration of a particular type of gaseous molecule. Hence, transfer can occur with (a) gas bubbles in a predominantly liquid phase, (b) liquid droplets in a gaseous phase, and (c) relatively large air-liquid interfaces, such as standing water surfaces.

Lewis and Whitman (18) postulated that two films, one liquid and one gas, restricted the passage of gas molecules between the liquid and gaseous phases. Where the solubility of gases is low, such as with CO_2 and O_2, the rate of gas transfer may be expressed by Equation 1.

$$\frac{dc}{dt} = K_t(C_s - C_1) \quad (1)$$

where $\frac{dc}{dt}$ = rate of change of concentration

K_t = transfer coefficient incorporating the specific area of the gas/liquid interface

C_s = saturation concentration of dissolved gas

C_1 = actual concentration of gas dissolved in the liquid

For low solubility gases, the liquid film offers the most resistance to gas transfer. Stirring or agitation of the liquid reduces thickness of the liquid film, thus promoting greater gas transfer (i.e., a larger K_t).

The two common methods of oxygenating activated sludge are (a) diffusion and (b) mechanical agitation. In a diffused air system, oxygen transfer takes place in three distinct phases: bubble formation, bubble rise, and bubble collapse. During the time the bubbles are in contact with the liquid, there is a continuous transfer of oxygen from the air through the interfacial film to the liquid. Since the coefficient K_t is proportional to the specific area of the gas/liquid interface, the size and number of bubbles are important criteria with respect to optimal oxygen transfer; thus, more numerous, smaller bubbles are inherently more efficient than coarse, large bubbles. In a mechanical aeration system, oxygen is transferred to the liquid by exposing the liquid to the atmosphere through turbulent mixing. Consequently, the efficiency of mechanical aeration is largely dependent upon the amount of turbulence created per unit of power.

Oxygen Requirements

In the aeration of a mixture of primary effluent and return activated sludge, the amount of oxygen required depends upon the quantity of carbonaceous BOD_5 to be oxidized, the relative amount of endogenous respiration taking place, and the required degree of nitrification.

In normal activated sludge treatment, when nitrification is not required, the amount of oxygen needed to oxidize the BOD_5 can be calculated by the following equation:

$$B = X(BOD_5) \quad (2)$$

where B = oxygen required for carbonaceous oxidation, mg/l or ppm
X = a coefficient
BOD_5 = 5-day biochemical oxygen demand

The coefficient X relates to the amount of endogenous respiration taking place and to the type of waste being treated. For normal domestic wastewater, the X value would range from a low of 0.5-0.7 for high rate activated sludge systems to a high of 1.5 for extended aeration. For conventional activated sludge systems, X can be taken as 1.0.

In the case of nitrification, the oxygen requirement for oxidizing ammonia must be added to the requirement for BOD removal. The coefficient for nitrogen to be oxidized can be conservatively taken as 4.6 times the ammonia content to obtain the nitrogen oxygen demand (NOD), and the value of X in Equation 2 can be assumed to be approximately 1.0. This yields the following oxygen requirement:

$$W = BOD_5 + NOD \qquad (3)$$

where W = the total oxygen demand, ppm, and

NOD = oxygen required to oxidize a unit of ammonia, taken as 4.6 times the total Kjeldahl nitrogen (organic plus ammonia nitrogen)

Since aeration devices are rated using tap water at standard conditions, the rated performance of the aerator must be converted to actual process conditions by the application of temperature corrections and by factors which relate waste characteristics to tap water characteristics. These factors are:

1. Temperature corrections, made by the factor $1.024^{(T-20)}$, where T = process temperature in degrees C.

2. The α factor (the ratio of oxygen transfer in wastewater to that in tap water), represented by:

$$\alpha = \frac{K_t \text{ (process conditions)}}{K_t \text{ (standard conditions)}} \qquad (4)$$

   Values of α can vary widely in industrial waste treatment applications, but for most municipal plants, it will range from 0.40 to 0.90.

3. The β factor (the ratio of oxygen saturation in waste to that in tap water at the same temperature). A value of 0.95 is commonly used.

The actual amount of oxygen required (W) can be determined from the amount transferred under test conditions (W_0) by equation (5), taken from Reference 1:

$$W = W_0 \, \alpha \left(1.024^{T-20}\right) \left(\frac{C_s - C_1}{9.2}\right) \qquad (5)$$

where W = oxygen transferred at process conditions, lb/day

W_0 = oxygen transferred at standard conditions, lb/day (T = 20C, DO = .01 ppm, tap water)

T = process temperature, degrees C

C_s = oxygen saturation in water at temperature T, ppm

C_1 = process dissolved oxygen level, ppm

The above result may be converted to kg/s units by multiplying answer by 5.250×10^{-6}.

Where nitrification is desired, the process dissolved oxygen level (C_1) must be set high enough to prevent inhibition of nitrification rates (4). For this purpose, a minimum value of 2.0 ppm is recommended. This value is also applicable under peak diurnal load conditions, and the practice of allowing the DO to drop below 2.0 ppm under peak is not recommended.

Using typical values for domestic sewage ($\alpha = 0.9$, $\beta = 0.95$, $C_1 = 2.0$, $T = 21$ and $C_s = 9.0$), the relationship between oxygen required under test conditions and that required under actual process conditions is: $W = W_0/1.5$. W_0 can be converted to hp requirements for mechanical aerators or to volumetric air flow rates for diffused air plants. According to Aberley (1), the latter is accomplished by solving Equation 6.

$$Q_A = W_0 \left(\frac{100}{23}\right)\left(\frac{1}{.075}\right)\left(\frac{1}{1440}\right)\left(\frac{100}{e}\right) = \frac{4.63}{e} \; W_0 \qquad (6)$$

where Q_A = air flow, cfm (60°F, 14.7 psia)

e = aerator rated oxygen transfer efficiency at standard conditions, percent

air composition = 23 percent oxygen, weight basis

air density = .075 lb/cf

The above result may be converted to m^3/s by multiplying answer by 4.719×10^{-4}.

Applying the above equation to diffusers of various efficiencies produces air rates from 94-38 m^3/kg (1500 to 600 cubic feet per lb) BOD_5 + NOD corresponding to diffuser efficiencies of 6 to 15 percent (1) (Figure 8).

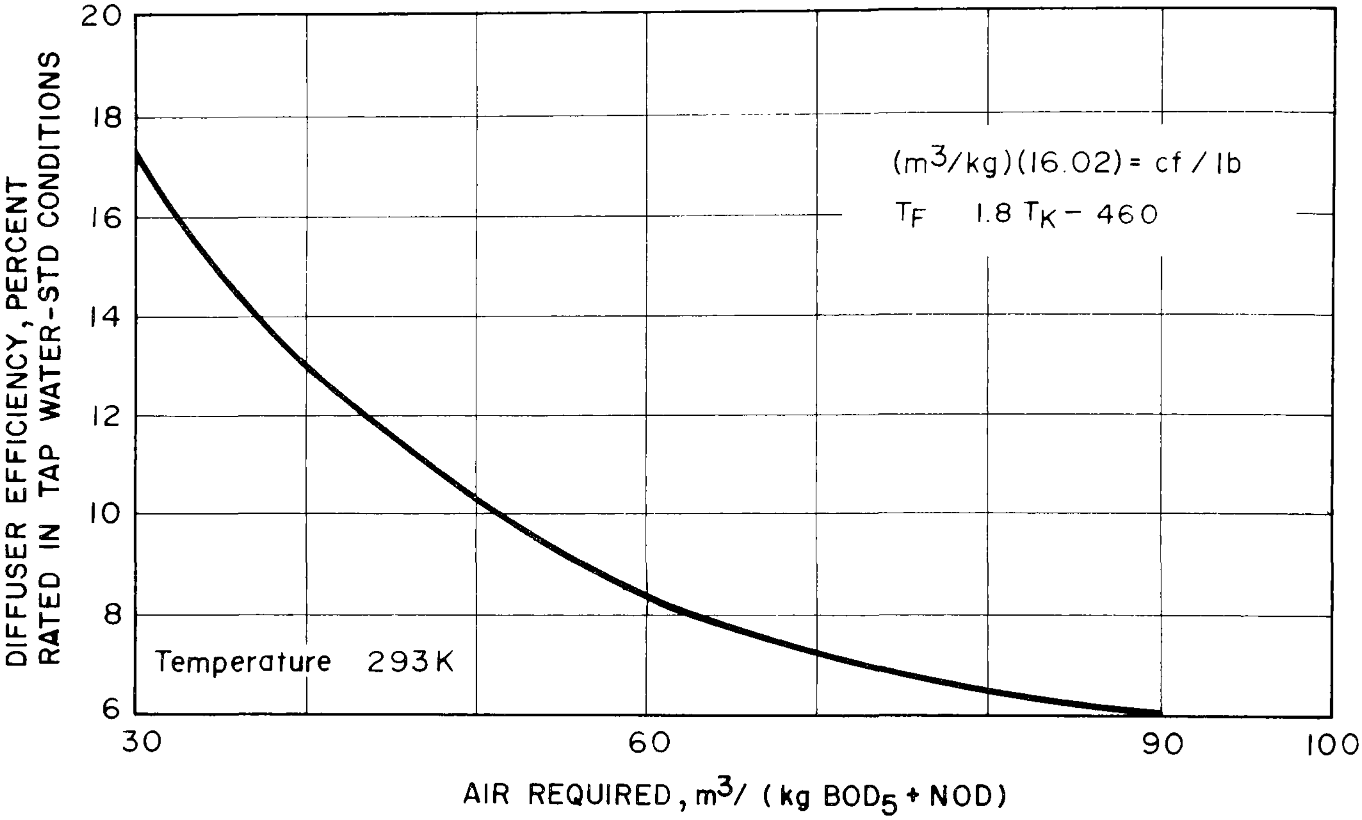
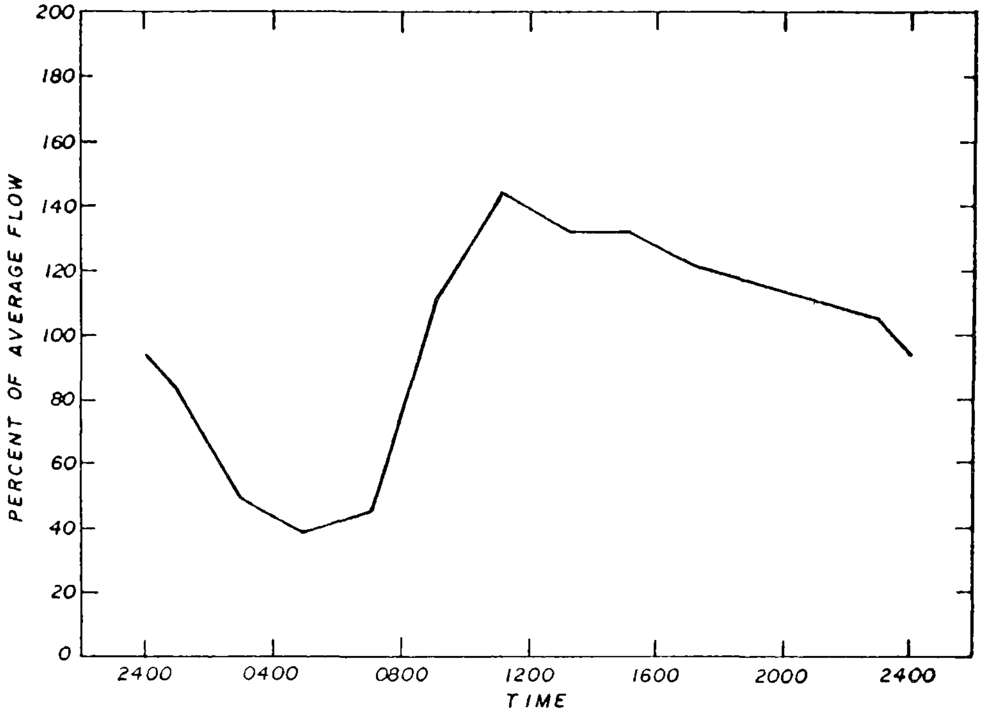


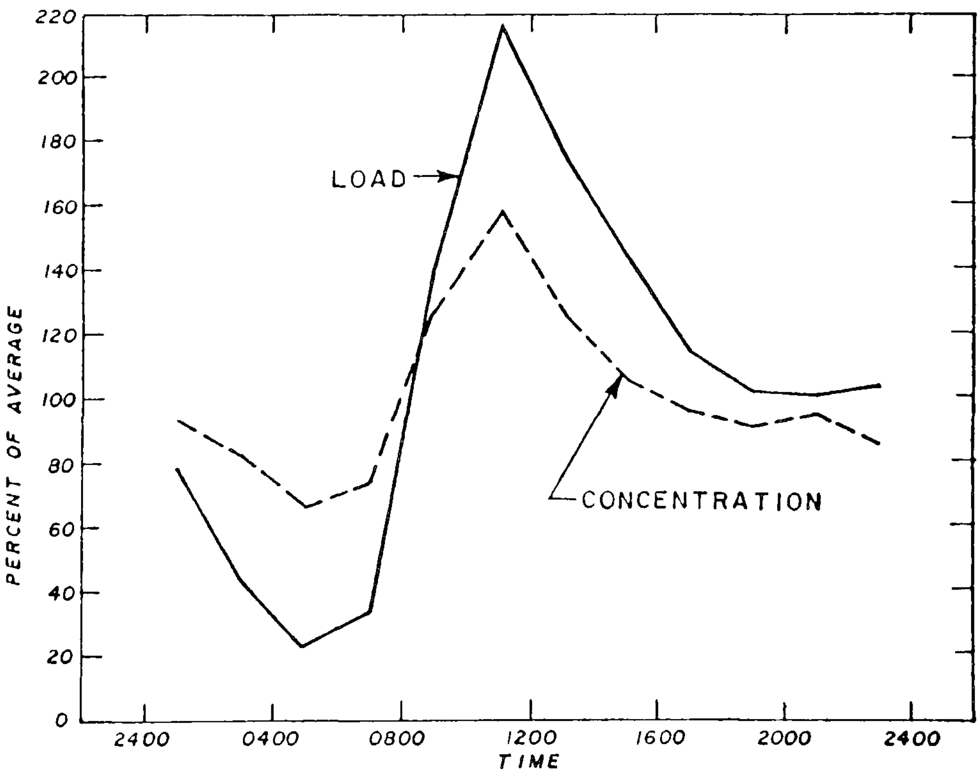
Figure 8. **Relationship of aeration air requirements for oxidation of carbonaceous BOD and nitrogen (4).**

Diurnal load variations are an important concern in designing air supply systems. Hanson, et al, (11) reported substantial diurnal variations in BOD_5, total nitrogen, and ammonia nitrogen in the influent to the Mason Farm Plant in Chapel Hill, North Carolina. Diurnal variations in wastewater flow and nitrogen load for that plant are shown in Figure 9. Total nitrogen was found to vary between 26 percent of average and 217 percent of average in a 24-hour period, and ammonia nitrogen ranged from 30 to 223 percent of average; BOD loading ranged from 13 to 190 percent of the daily average, while wastewater flow rate varied between 39 and 144 percent of average flow.

The North Carolina data do not show the relative fractions of soluble and insoluble BOD_5. Hence, it is not possible to accurately estimate the percentage of influent BOD leaving primary clarification for subsequent



DIURNAL VARIATION IN WASTEWATER FLOW



DIURNAL VARIATION IN NITROGEN LOAD AND CONCENTRATION

Figure 9. Diurnal variations in load at the Chapel Hill, N. C Treatment Plant (11).

secondary treatment. On the other hand, nitrogen is largely soluble; thus, primary influent nitrogen loadings are approximately equal to secondary treatment process influent nitrogen loadings.

It is important to note in Figure 9 that fluctuations in concentration very nearly match diurnal variations in wastewater flow. The combined effect of diurnal variations in flow and concentration is a fairly dramatic fluctuation in total nitrogen load. Parker, et al., (4) have shown maximum hourly ammonia loads nearly 2-1/2 times as great as average daily ammonia loads for plants with maximum hourly flows of only 1.5 to 2 times the average daily flows, as shown in Figure 10. The complete range of diurnal load variations can be quite extreme. In Figure 11, peak to minimum hourly load ratios are plotted against the flow peaking factor; ratios as high as 10 to 1 have been observed. The extra aeration capacity and tankage required for handling diurnal variations, where nitrification is practical, may dictate in-plant flow equalization in many instances. The reductions in capital and operating cost of aeration and tankage in aeration facilities must be compared with the cost of flow equalization to determine applicability to specific cases. Design data for flow equalization are contained in Chapter III of Reference 31.

To conserve energy, careful consideration must be given to maximizing oxygen utilization per unit of input power. Under significant load variation, aeration systems should be designed to match the load variations, while economizing on power input. Designing an aeration system to provide for maximum hourly demand twenty-four hours a day, without turndown capability, results in overaeration most of the time, with wasteful losses of power.

As an example of the importance of large aeration capacity to achieve nitrification, let us assume a plant having an average flow of 0.44 m^3/s (10 mgd), a raw sewage BOD_5 of 250 ppm, an average NH_3 concentration of 30 ppm, a peak NH_3 concentration of 60 ppm, a primary BOD_5 removal of 35 percent, an aerator efficiency of 10 percent, and an effluent BOD_5 of 20 ppm. For such conditions, the air delivery capacities are as follows: (a) no nitrification, 4.72 m^3/s (10,000 cfm) and (b) complete nitrification, 13.7 m^3/s (29,000 cfm). Thus, the aeration capacity required for complete nitrification under peak ammonia input is about three times that needed for carbonaceous oxidation. This is one reason why many aeration plants designed for conventional air rates are unable to nitrify.

AERATION TECHNIQUES

Two basic aeration methods are normally used: (a) diffused aeration, where the air is introduced into the mixed liquor through a series of diffusion devices; and (b) mechanical aeration, where air is introduced to the mixed liquor by exposing the liquid to the air.

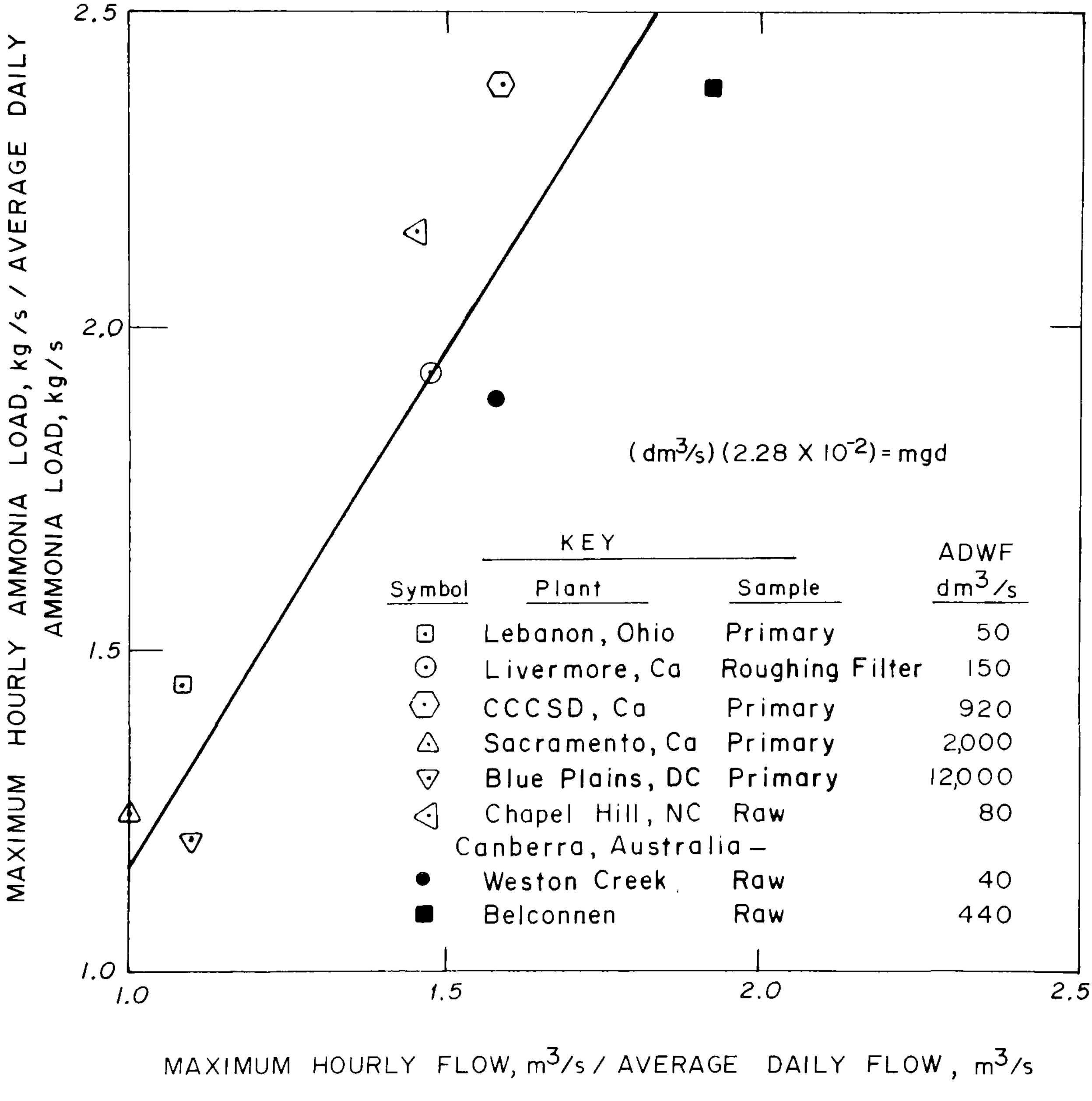


Figure 10. Relation between ammonia peaking and hydraulic peaking loads for treatment plants with no in-process equalization (4).

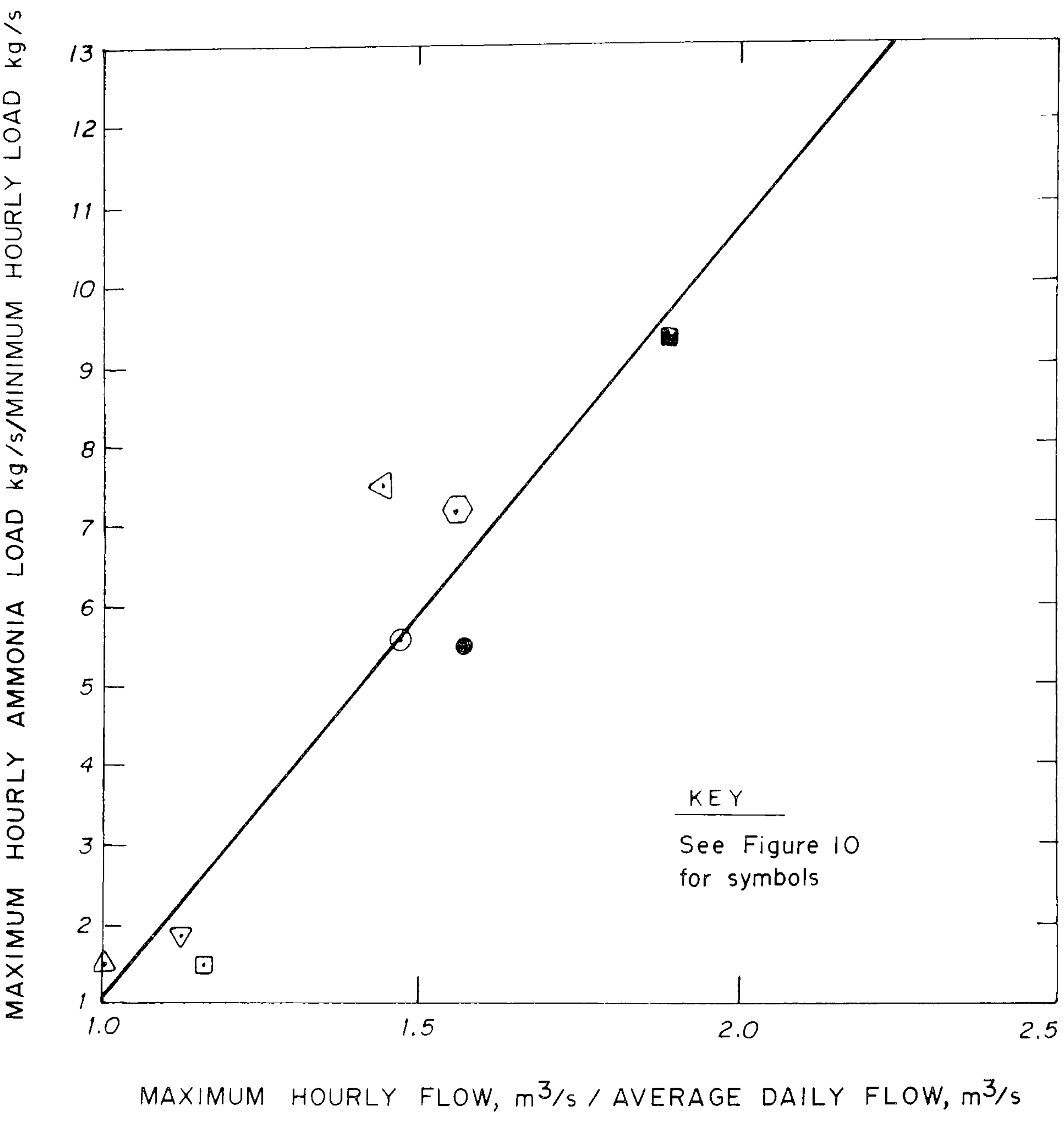


Figure 11. Relationship of maximum/minimum nitrogen load ratio to maximum/average flows (4).

Diffused Aeration

The term diffused aeration is applied to any process where air from an external source is injected into the oxidation tank through a diffusion device. The diffusion device can be anything from a perforated pipe to a complex diffuser. Diffused aeration systems are broadly segregated into two classifications; coarse bubble diffusion and fine bubble diffusion. Each of these main classifications contains a number of subclassifications.

Coarse Bubble Diffusers--

As the name implies, a coarse bubble diffuser releases relatively large air bubbles into the mixed liquor. Coarse bubble diffusers fall into four general categories: orifice, valve, shear, and shallow submergence.

Orifice diffusers--Orifice diffusers have one or more small openings for the passage of air. Typically, the openings are 3.2-13 mm (1/8 to 1/2 inch) in diameter. The diffusion units are generally made of molded plastic and are either screwed or clamped to the air header pipe. Two typical types of orifice diffusers, together with head loss characteristic curves, are shown in Figure 12.

Valve diffusers--Valve type diffusers contain a built-in valve that closes when air flow is stopped. Two types of valve diffusers are shown in Figure 13. The Eimco diffuser employs a neoprene disc flapper as the valve, while the PFT unit utilizes a plastic ball. In the latter, the air passage area is the space between the ball and ball seat. This can be adjusted in size using different size spacers. The main advantage of valved orifice diffusers is their ability to prevent backflow of mixed liquor into the air header on loss of air pressure.

Shear diffusers--Shear diffusers, pictured in Figure 14, use counterflow of air-liquid streams to shear large air globules into smaller bubbles. Shear diffusers are difficult to attach to removable pipe headers and are, therefore, generally limited to applications where they can be fixed to the bottom of the tank.

Shallow submergence diffusers--Air diffusers are normally installed at or near the bottom of the oxidation tank. To overcome the problem of injecting air at those depths, the Inka aeration system, shown in Figure 15, was developed. This system employs a series of perforated pipes located about 0.9 m (three feet) below the water surface. A baffle is installed to force the desired circulation pattern. The major advantage of this system is the low air pressure required. Thus, fans may be substituted for more costly blowers.

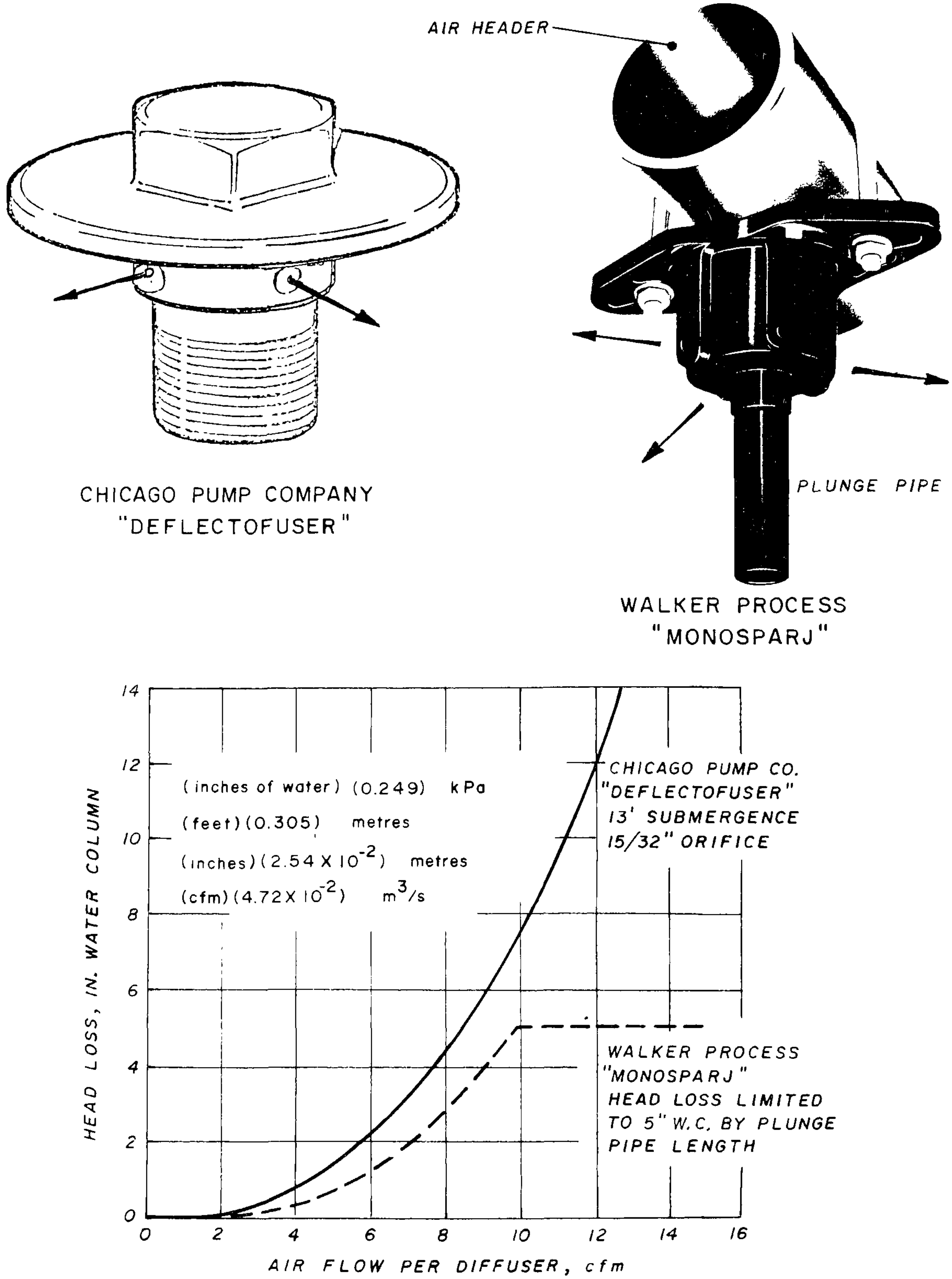
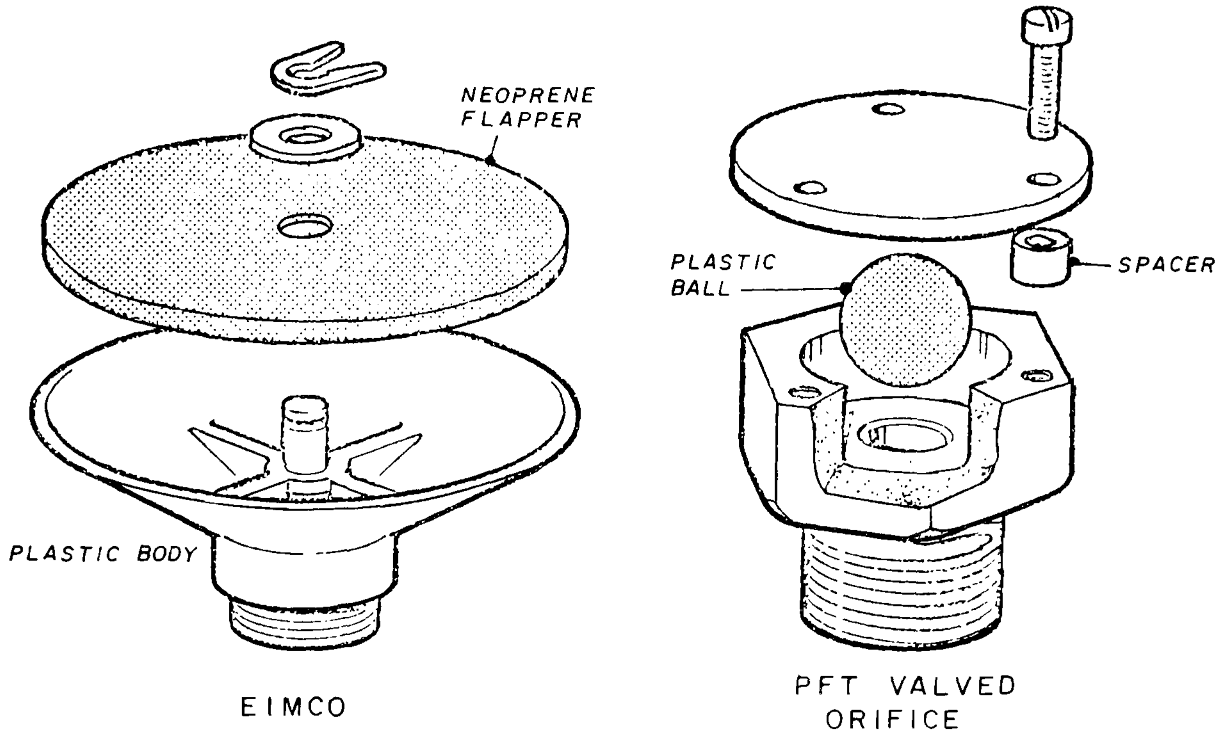


Figure 12. Characteristics of orifice-type coarse bubble diffusers (1).



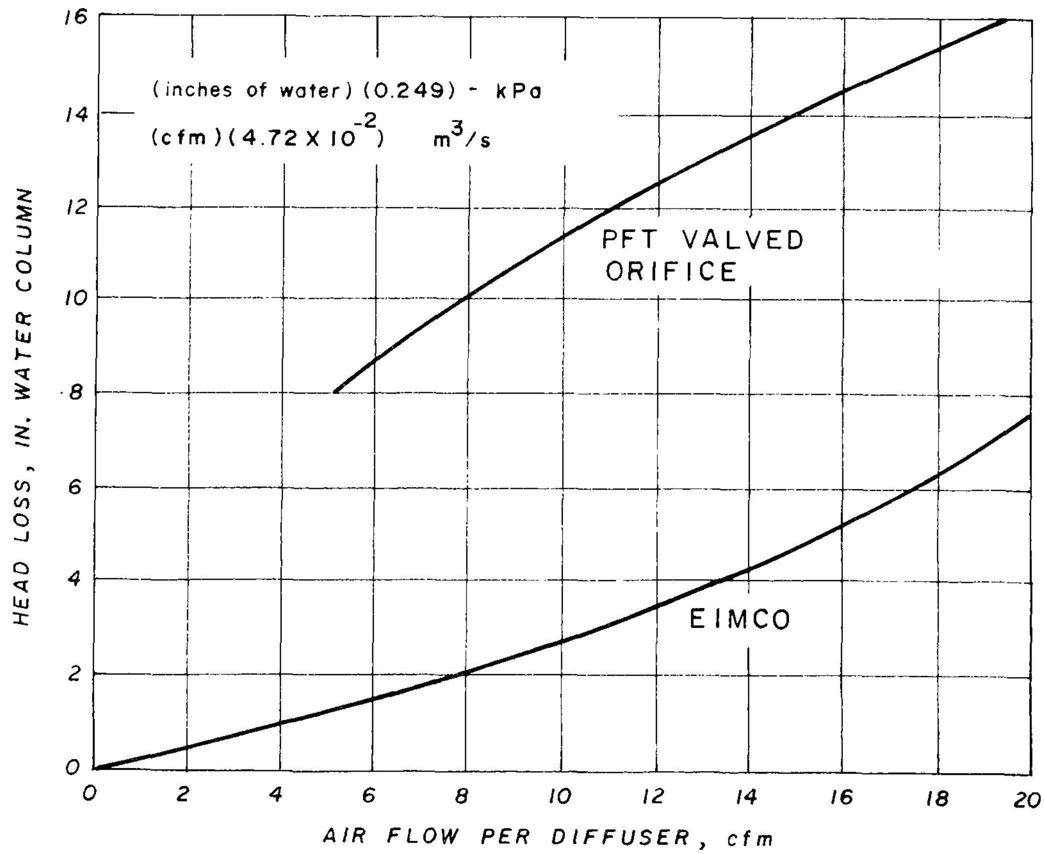


Figure 13. Characteristics of valve-type coarse bubble diffusers (1).

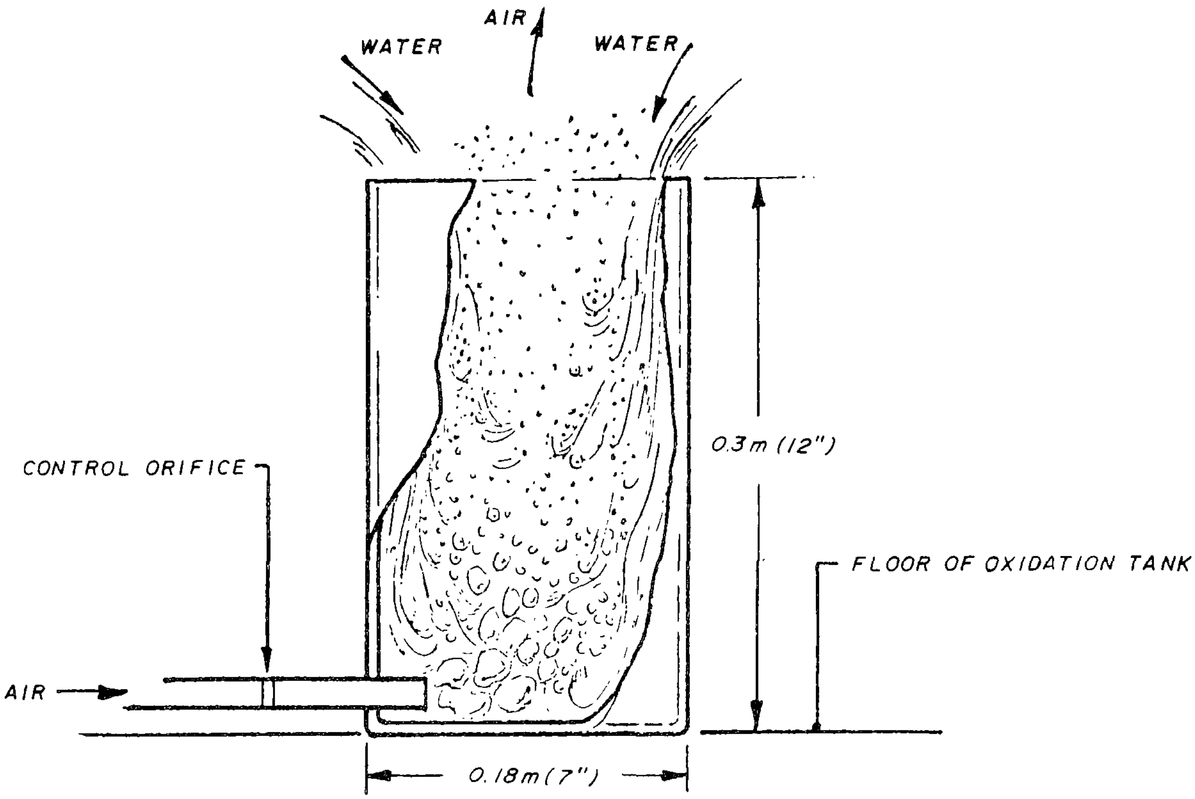


Figure 14. Typical shear-type coarse bubble diffuser (1).

Fine Bubble Diffusers--

Aeration by fine bubble diffusers is characterized by the production of very small air bubbles, which impart a gentle movement to the mixed liquor in lieu of the turbulence associated with coarse bubble diffusers. Diffusion devices in fine bubble diffuser plants are invariably of the porous ceramic type, composed of silicon dioxide or aluminum oxide grains held in a porous mass with a ceramic binder. Porous diffusers are available in a variety of shapes, with the most common being flat plates, hollow tubes, and domes. Head loss characteristics of all shapes of porous diffusers are comparable, but oxygen transfer efficiencies are not necessarily the same due to a number of variables, particularly bubble coalescence, which is a function of diffuser shape.

Porous plates are rated on the basis of "permeability", or the volume of air in cubic feet per minute which is passed through 9.3 dm^2 (one square foot) of diffuser 2.5 cm (one inch) thick when tested dry at a 500 Pa (two-inch water column) differential pressure under standard conditions of temperature, pressure, and humidity. Permeabilities commonly range from 9-37 dm^3/minute (20-80 cfm/minute).

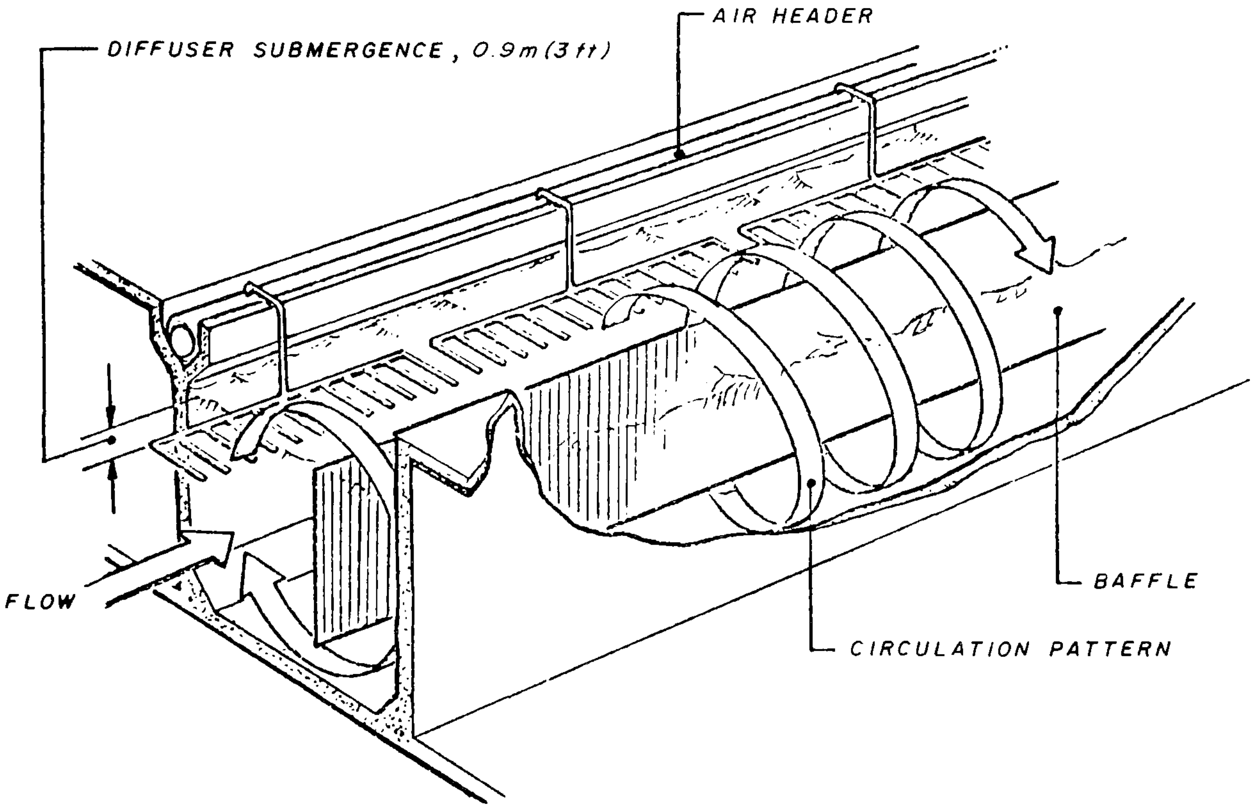


Figure 15. Shallow submergence aeration system (1).

Other types of fine bubble diffusers include Saran wrapped tubes and sock-type diffusers. Saran wrapped tubes are 0.61 m (24 inches) long by 76 mm (3 inches) in diameter and are formed by tightly wrapping Saran cord around a corrugated stainless steel core. An integral control orifice is provided and the bubble obtained is about the same size as that from a 19 $dm^3/$minute (40 cfm/minute) permeability ceramic tube. The sock-type diffuser was developed in an attempt to minimize clogging problems. The sock is made of plastic fabric and fitted over an opening in an air header, which is equipped with a control orifice. When air is introduced, the sock fills out. The flexing action is designed to reduce clogging.

Diffuser Arrangement--

The first question to answer in selecting a good diffuser arrangement is whether the operator must remove the diffusers without emptying the tank. All diffusers require maintenance, particularly fine bubble diffusers. If oxidation tanks cannot be taken out of service, the diffusers should be easily removable for maintenance outside the tank. In large plants with multiple tanks, fixed diffusers are acceptable where it is possible to drain a tank for maintenance without impairing plant treatment efficiency. However, in small plants, where only one or two tanks are provided, diffusers should be removable while the tanks are in service.

If diffusers must be removable while the tank is in service, flat porous plates cannot be used and the diffusers must be installed on pipe headers arranged in either a spiral-roll or cross-roll pattern (Figure 16). Either coarse or fine bubble diffusers can be installed in this manner providing they can be easily attached to the pipe header. Spiral-roll patterns are less desirable because of short circuiting and inferior oxygen transfer performance. These problems are partially overcome in the cross-roll configuration, which provides closely spaced air curtains, through which the mixed liquor must flow.

If fixed diffusers are used, a large variety of diffuser arrangements are available. Therefore, traditional configurations, such as spiral or cross-roll patterns, should be avoided in favor of more efficient arrangements. For example, recent experimental work at Milwaukee (15,16) and Melbourne (Aberley, R. C., Rattray, G. B., and Douglas, P. P., "Design and Performance Testing of Air Diffuser Units for Melbourne's South Eastern Purification Plant," unpublished paper, November 1972) has demonstrated that flat porous plates arranged over the entire tank bottom provide a much higher oxygen transfer capability than any other arrangement. The Milwaukee experiments even demonstrated that the old "ridge and furrow" diffuser pattern is more than twice as efficient as the modern spiral-roll arrangement.

At Milwaukee (15,16), full scale in situ oxygen transfer studies were made of seven different arrangements of fine bubble diffusers. The results of these tests are given below:

Diffuser pattern	Oxygen transfer efficiency 95% confidence range, percent
Porous tubes, spiral-roll	3.3 - 9.1
Porous tubes, cross-roll	4.7 - 7.7
Porous plates, ridge and furrow	8.0 - 26.2
Porous plates, crows foot	8.6 - 10.4
Porous plates, modified crows foot	9.3 - 11.5
Porous plates, transverse placement	10.3 - 12.3
Porous plates, longitudinal placement	11.4 - 14.4

This experiment was valuable in pointing out the importance of diffuser placement and it amply demonstrated that the placement of diffusers over the entire tank floor is the most efficient arrangement from the standpoint of oxygen transfer.

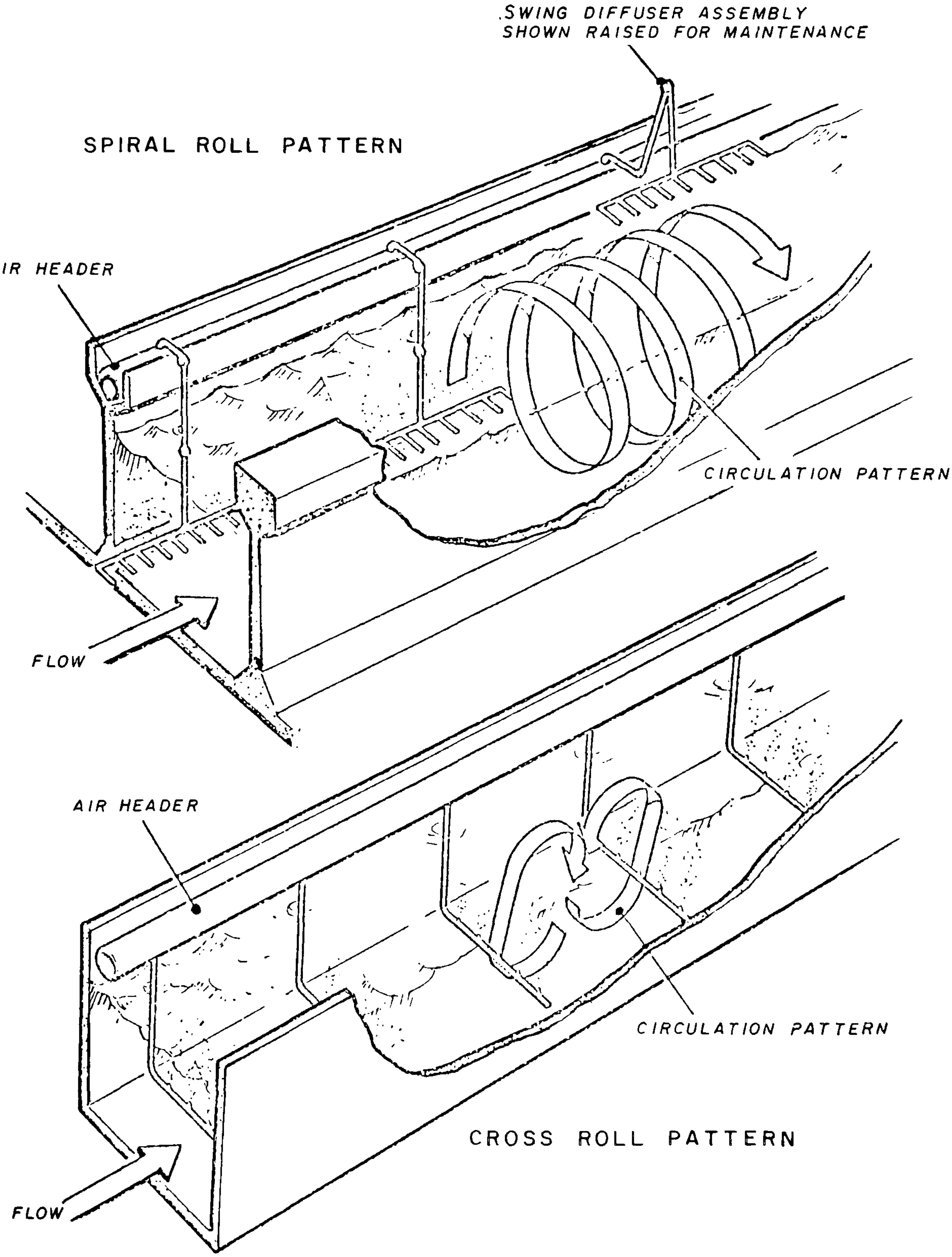


Figure 16. Spiral and cross roll diffuser arrangements (1).

The use of flat porous plates over the entire oxidation tank bottom as shown in Figures 17 and 18 eliminates tank geometry restrictions imposed by conventional spiral-roll oxidation tanks. Aberley (1) has shown that 0.36 m (14 inch) diameter porous plates, mounted flush with the tank bottom, give excellent performance at the South Eastern Purification Plant in Melbourne, Australia. A full-scale plenum unit was tested in a 4.6 m (15 foot) deep test tank in tap water with the results shown in Figures 18 and 19. Oxygen transfer efficiencies are corrected to standard conditions and indicate that the diffuser design is extremely efficient.

Deep Submergence Aeration

Primarily because the need to place diffusers near the tank bottom imposes economic limitations on blower selection, oxidation tanks have traditionally been restricted to a maximum depth of about 4.6 m (15 feet). Aeration at greater depths is desirable since greater oxygen transfer efficiency is possible with increased diffuser submergence (see Figure 19). With this incentive, Walker Process Equipment Company has developed a system, based on the airlift principle, to aerate deep tanks with medium pressure (41 kPa) (6 psi) blowers (30). Conventional circular eductor tubes used for air or gas lifting applications become increasingly inefficient as their size increases, because in large (up to 2.1 m) (7 foot diameter) tubes, the air-lifted mass in the center possesses no more energy than that at the lip of the tube. Consequently, the flow at the center has difficulty leaving the tube, while at the same time, its entrained air exhausts vertically, leaving the center portion of the mass virtually as an overburden. Tests have shown that airlifts remain efficient as long as the outflow is no further than 0.6 m (2 feet) in any direction. Thus, circular tubes larger than 1.2 m (4 feet) in diameter are less efficient than smaller tubes. Utilizing that principal, Walker Process designed a rectangular tube 1.1-1.5 m (3.5 to 5.0 feet) in width which can be as long as tank geometry requires, without loss of efficiency. Coarse bubble diffusers are installed at about middepth of the tube. In this manner, tanks up to 9.1 m (30 feet) deep can be efficiently aerated. The advantages are in greater oxygen transfer efficiency, reduced tank plan dimensions, and more economical tank construction. The manufacturer reports oxygen transfer efficiency in tap water at standard conditions to be from 12 to 14 percent. Figure 20 shows details of a typical deep submergence aeration system.

Aeration Blower Systems

An integral part of aeration systems is the air supply network, consisting of filters, blowers and the necessary ductwork, valving and controls to effectively distribute compressed air. Filters remove minute dust particles (aerosols) from the air flow, mainly to prevent clogging of the diffuser plates. Blowers compress the air, raising it to sufficient pressure to overcome hydrostatic head in the aeration tanks and losses in the delivery system. Air for

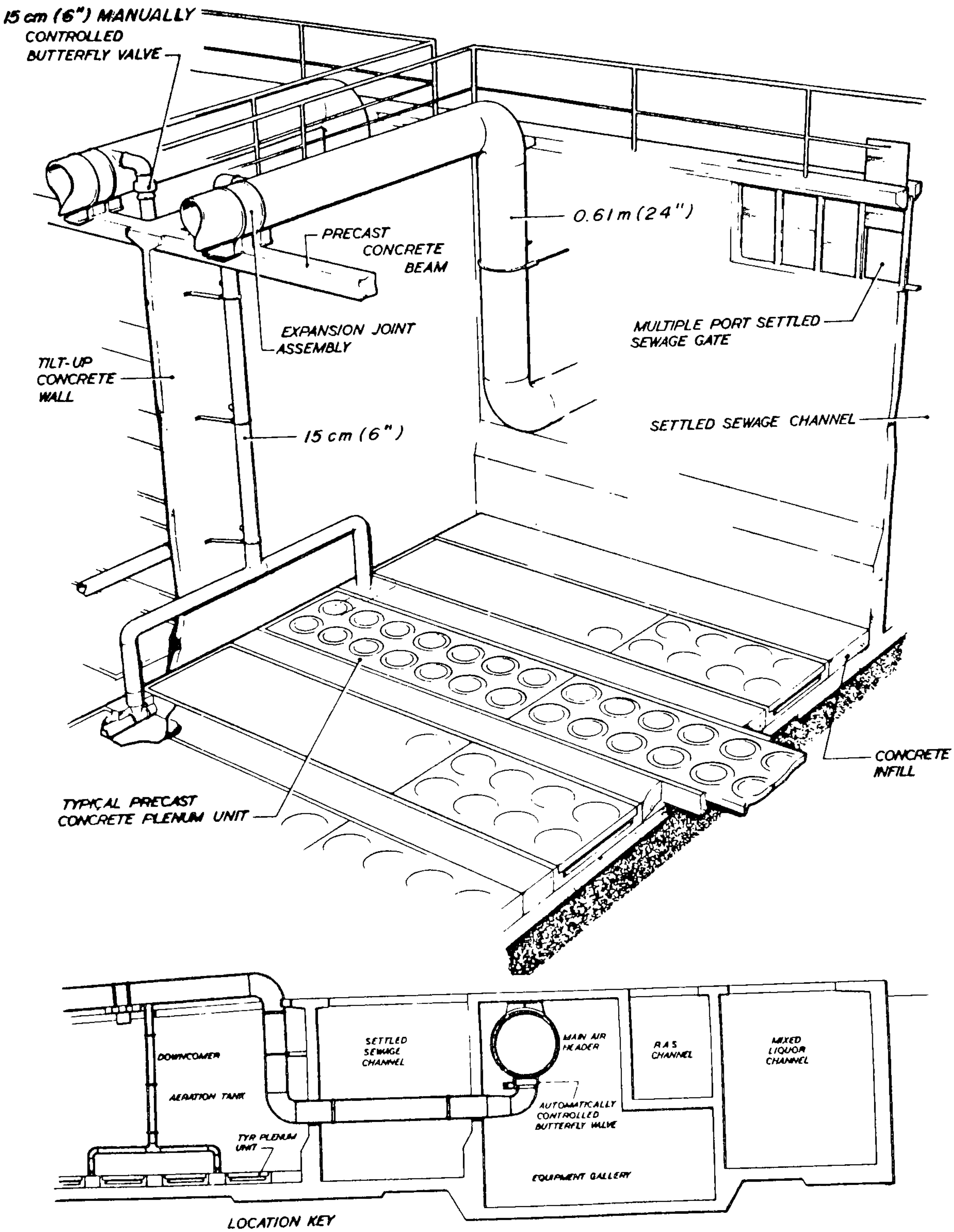
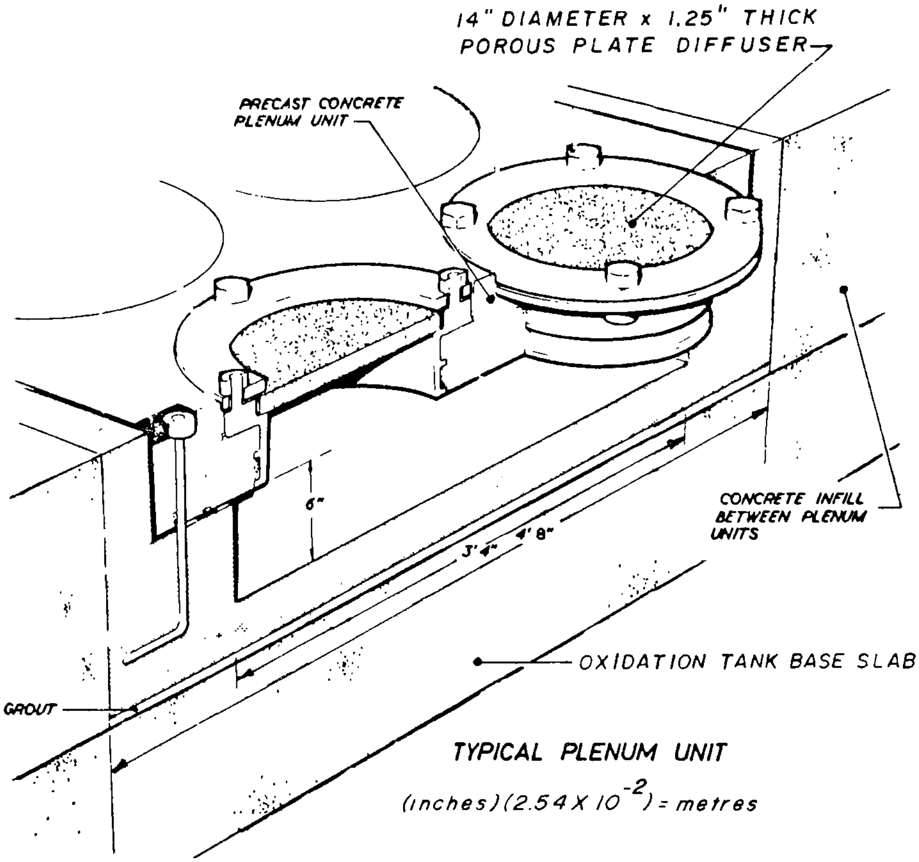
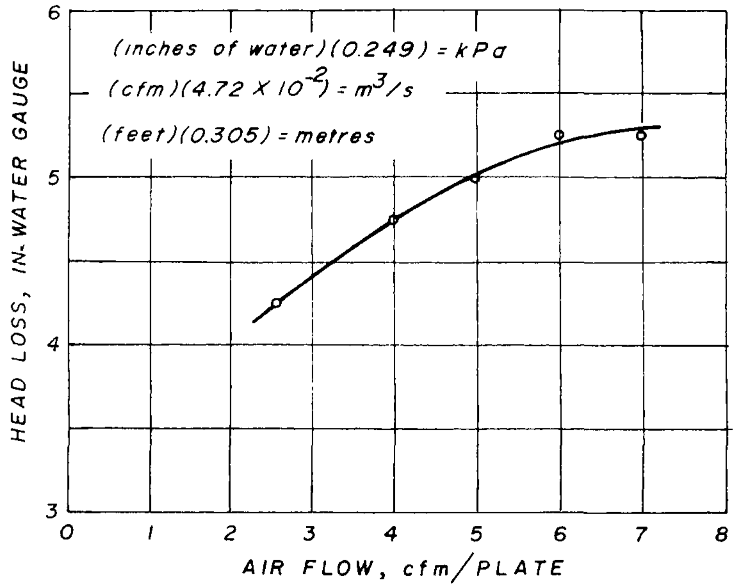


Figure 17. Aeration system - South Eastern Purification Plant, Melbourne, Australia (1).





HEAD LOSS THROUGH DIFFUSER PLATES WITH DRY PLENUM AT 10 FT DIFFUSER SUBMERGENCE

Figure 18. Characteristics of porous plate diffuser at the South Eastern Purification Plant, Melbourne, Australia (1).

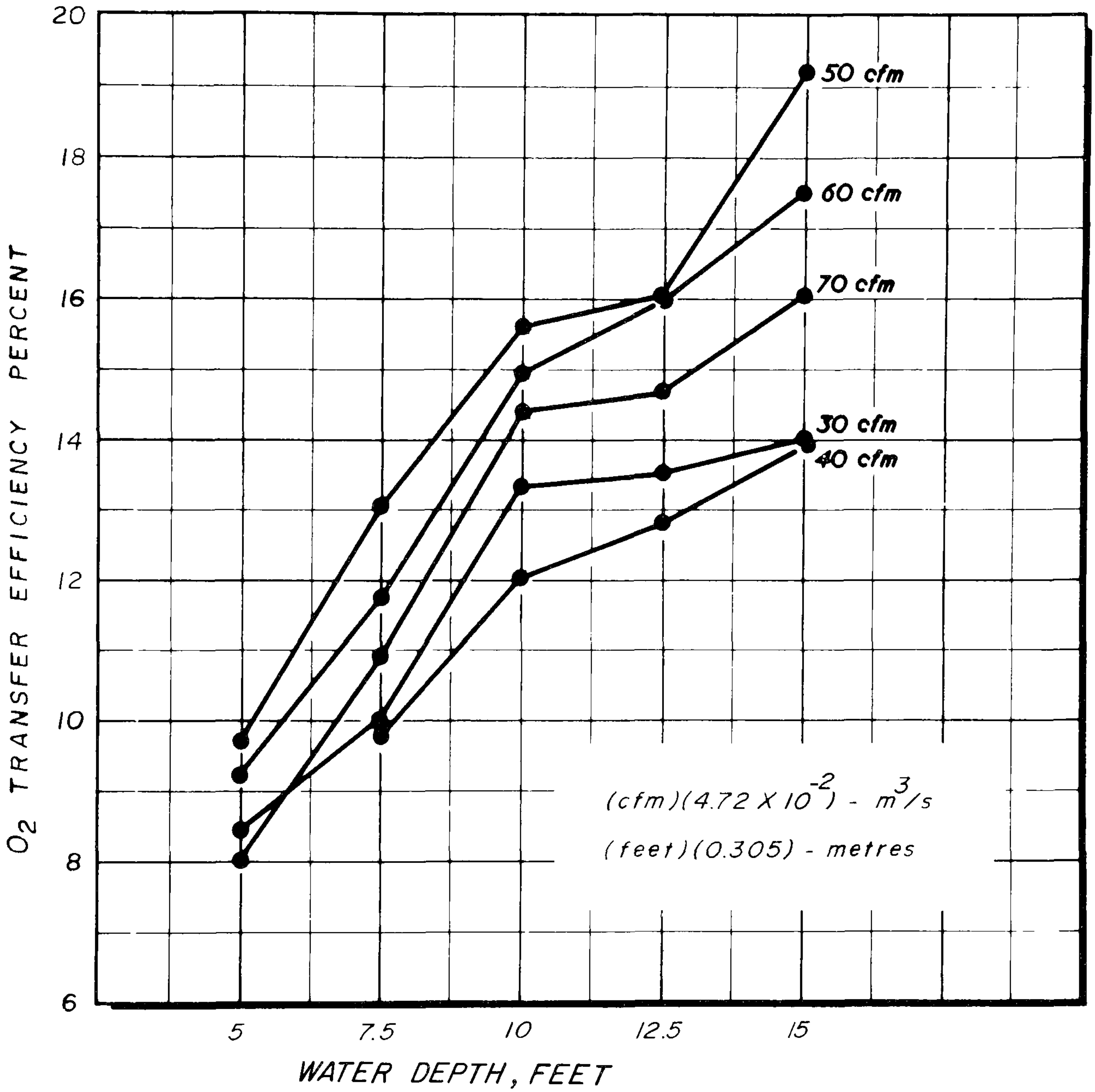
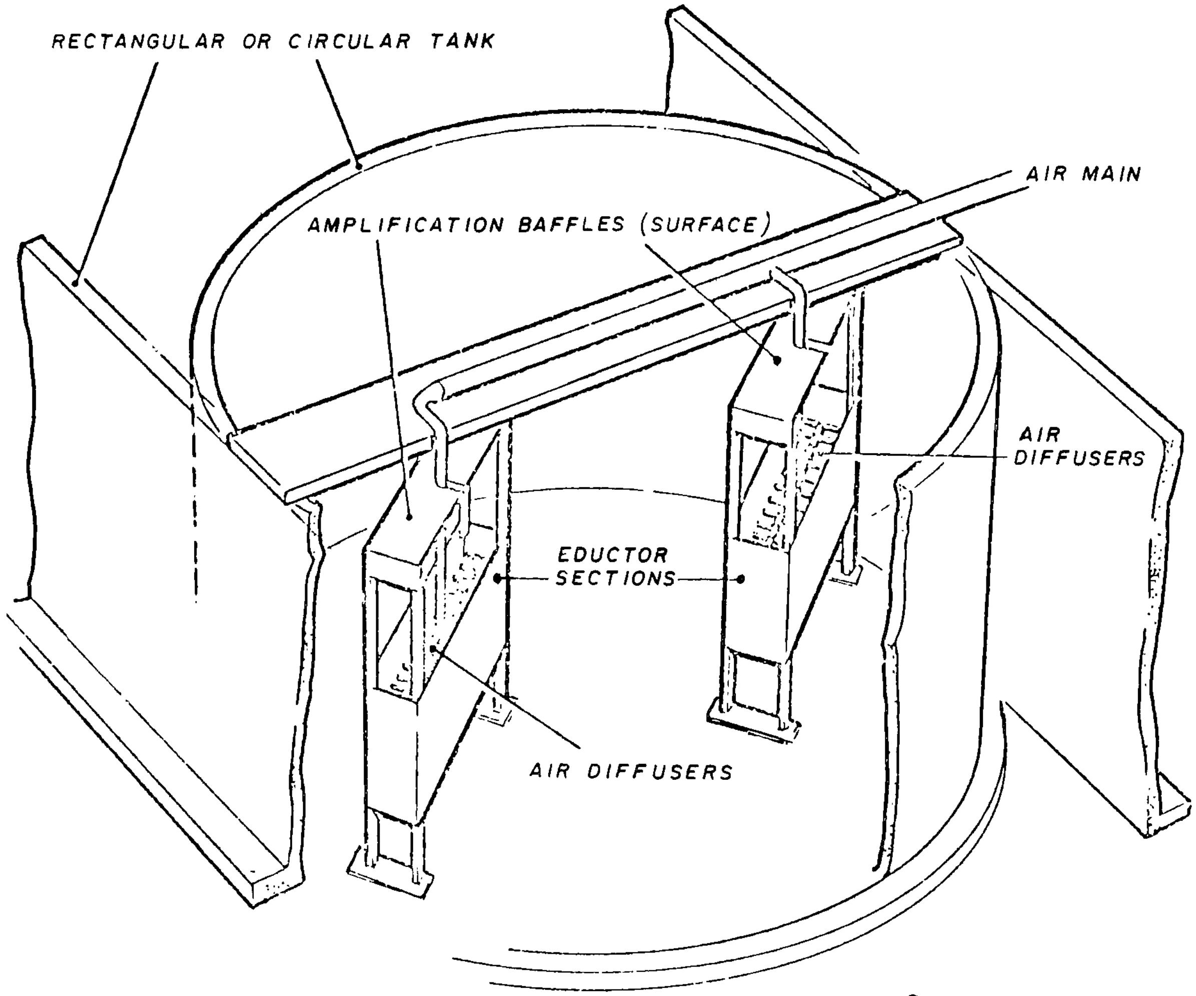


Figure 19. Oxygen transfer efficiency of diffusers at various flow rates and submergence (1).



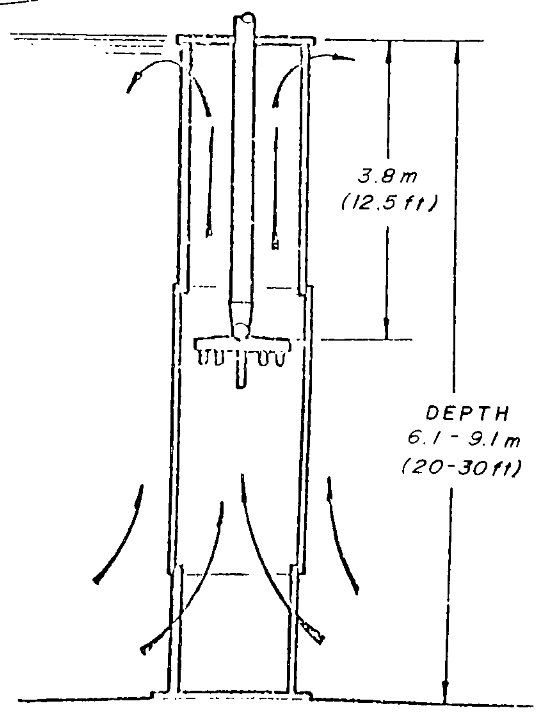


Figure 20. Details of Walker Process Equipment Company deep submergence diffusion system (1).

the activated sludge process has been furnished by almost every type of compressor developed to this date (10). In the past, a distinction was made between blowers and compressors relative to a discharge pressure of 276 kPa (40 psig). Modern applications over a wide range of pressures have made this distinction meaningless (29). Accordingly, the terms blowers and compressors are used interchangeably at the low discharge pressures encountered in sewage treatment plant aeration systems. However, the Compressed Air and Gas Institute recognizes compressor as being a more universally applied term. Three types of blowers or compressors commonly used in activated sludge plants are (a) positive displacement, (b) centrifugal, and (c) axial. Table 1 summarizes application information and polytropic efficiencies of various types of blowers used in sewage plant aeration systems. Polytropic efficiency indicated in Table 1 is defined as: the ratio of the polytropic compression energy transferred to the gas to the actual energy transferred to the gas, where compression energy is expressed in the form PV^n = a constant, and P is pressure, V is volume and n is the polytropic exponent. The polytropic exponent applies to the actual process, including heat transfer and friction, in contrast to the isentropic exponent, k, which applies to the ideal, frictionless adiabatic process (29).

In the application of a blower to any practical situation, it is essential to consider the characteristics of the load, as well as those of the blower. Pressure required to force a quantity of air through any system is dependent on two main components: static head and frictional resistance. In the case of the aerator system, static head is imposed by the depth of mixed liquor above the diffusers, while frictional resistance is imposed by the length of pipework, bends, valves, etc., through which the air must pass and also by the diffusers themselves. Static head is almost constant (although small changes of liquid depth in the tank will cause minor variations), but frictional resistance increases according to the square of air flow. A typical pressure resistance/air flow curve is shown in Figure 21. In this figure, line C-D represents static head; curve E-F represents frictional resistance; and the resultant of these two components is represented by curve C-G.

To explain the application of a blower to a given service, the performance curve A-B is superimposed on the demand or load curve C-G, as illustrated in Figure 22. With this combination of blower and load, the capacity handled will come at the intersection of the two curves, i.e., point H. This is the only point at which the blower will operate in that system, and this determines air flow and back pressure.

Positive Displacement Blowers--

The positive displacement blower most frequently used in diffused aeration systems is the rotary, two impeller, positive displacement blower. This blower is a constant volume, variable pressure machine. It employs two symmetrical figure eight shaped impellers that rotate in opposite directions

TABLE 1. APPLICATION CHART FOR BLOWERS USED IN SEWAGE PLANT AERATION SYSTEMS[a]

Volume range in standard m^3/s (scfm)	Blower type	Polytropic efficiency percent[b]	Remarks
Up to 7.1 (15,000)	Positive displacement lobe type	71[c]-78	Low first cost
	Multistage vertically split centrifugal	71-77	
7.1-22 (15,000-47,000)	Integral-gear, single-stage centrifugal	76-79	Low cost, minimum spaces
	Pedestal type, single-stage centrifugal	77-80	Intermediate cost, more space
	Multistage, horizontally split centrifugal	78-80	Traditional approach, costly
22-47 (47,000-100,000)	Pedestal type, single-stage centrifugal	77-80	Low first cost
	Multistage, horizontally split centrifugal	78-80	Traditional approach, costly
47-71 (100,000-150,000)	Pedestal type, single-stage centrifugal	77-80	Low first cost
47-94 (100,000-200,000)	Axial	82-83	High first cost, high efficiency

[a] Data extracted by permission from Reference 10.

[b] See text for definition of polytropic efficiency.

[c] For low capacities such as 0.9 m^3/s (2,000 scfm).

in a cylinder. Compression occurs by entrapment of the air by the rotating lobes. As each lobe of an impeller passes the blower inlet, it traps a volume of air equal to one-fourth of the total blower displacement. Timing gears maintain the blower impellers at minute clearances from each other. During operation a certain amount of air, defined as slip, leaks around the impellers back to suction. Slip is constant for a given blower at a given discharge pressure. Thus, the blower should be operated at high speed to maximize the volumetric efficiency.

The rotary, positive displacement blower can be capacity controlled by (a) providing a variable speed transmission or driver, (b) using multiple units, (c) blowoff control, and (d) recirculating discharge to suction. The blower automatically furnishes variable pressure output since it "floats" on

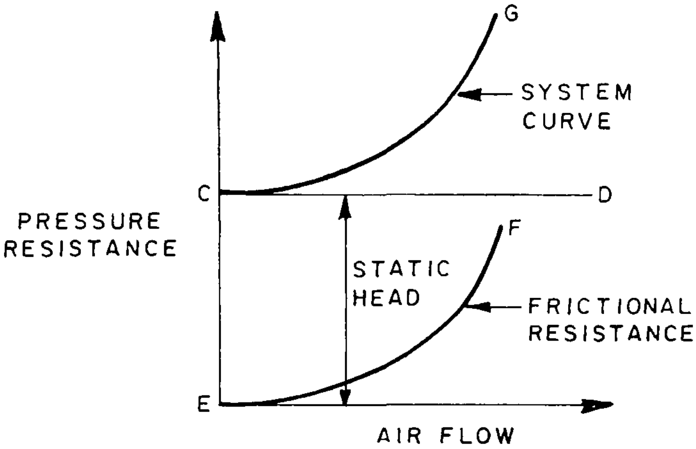


Figure 21. System characteristic curve.

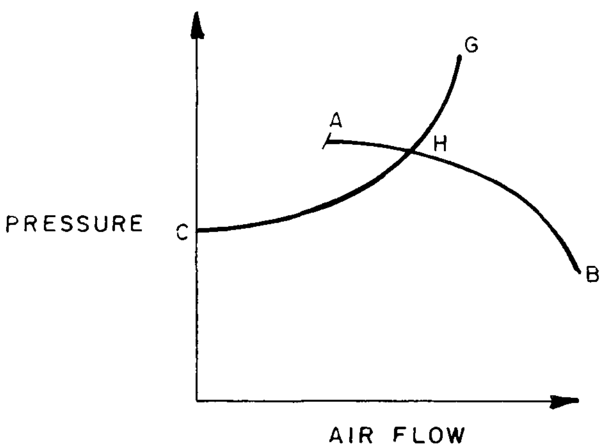


Figure 22. Blower/system curves.

the line, developing a pressure equal to the back pressure of the system. Good installation practice calls for use of a relief valve to protect the blower and motor from damage due to a pipeline restriction or closure (29).

Centrifugal Blowers--

The characteristic curve of a typical centrifugal blower is illustrated in Figure 23. This shows how blower output varies according to back pressure exerted on the discharge side. The curve shown is for a blower driven at constant speed and without inlet guide-vane throttling. Note that the curve (A-B) is broken off where it becomes nearly horizontal. This is the point where unstable "surge" conditions develop.

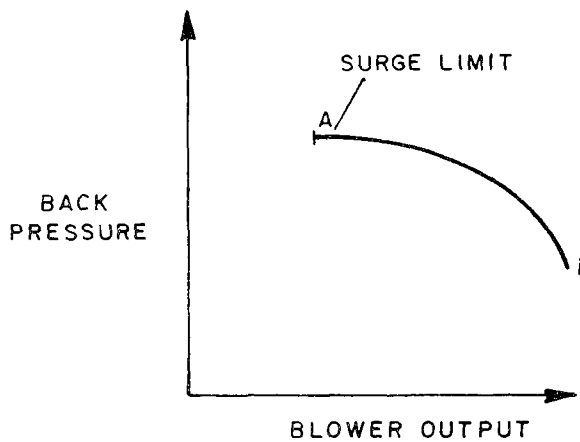


Figure 23. Blower characteristic curve.

In the example given previously (Figure 22), point H represents the maximum blower output capability in that system, i.e., with the blower running at its rated speed and with no upstream or downstream valves throttled. If it is wished to reduce blower output (for example, when activated sludge organisms require less air), three methods of control might be used: discharge throttling, blower speed variation, or inlet throttling.

Discharge throttling--The effect of discharge throttling on a typical blower is shown in Figure 24. Curve C-G represents the load curve of the unthrottled system (as before), with point H representing blower delivery under these conditions. Curve C-G' shows the modified load curve that would be obtained by throttling a valve installed in the delivery pipework, and point H' represents blower output under these new conditions. Curve C-G" and point H" show the effect of throttling the delivery somewhat further.

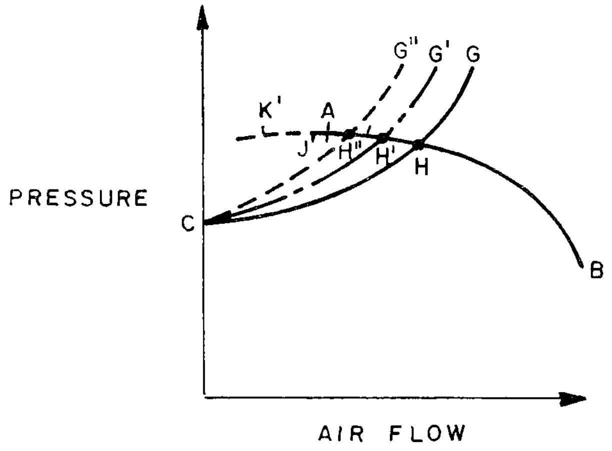


Figure 24. Discharge throttling control.

Although discharge throttling can be used quite effectively to regulate blower output over a limited range, this control method has two disadvantages. The first is that it is not efficient, since this artificially-created resistance represents an irrecoverable loss of power (energy being dissipated in the discharge valve), and the second is the risk of creating "surge" conditions.

If the blower's characteristic curve is studied (see Figures 23 and 24), it will be observed that its slope decreases as back pressure is increased to reduce blower output until, at point J, the direction of slope reverses, as indicated in Figure 24. In practice, however, this situation is impossible to achieve, since the blower would enter an unstable part of its operating range, known as the "surge" zone.

If the blower is allowed to operate at a point on its curve close to point J, a very minor variation in back pressure could cause the blower to operate at two points on its curve--A and K'--i.e., at two different outputs (see Figure 24). If this condition develops, output of the blower will fluctuate between these limits, causing back pressure oscillations which, in turn, cause further air flow variations. Output of the blower is virtually uncontrollable in this range. If allowed to continue, this surging might result in damage to the blower.

To avoid the surge zone, blower delivery must be kept above about 60 percent of rated output. Since discharge throttling would produce large energy losses, other control methods are usually more attractive for regulating blower delivery.

Blower speed variation--Another method of regulating blower output is to vary blower speed. Effects of variable speed control on a typical centrifugal blower are illustrated in Figure 25. It should be noted that minor variations in motor speed such as could be caused by slight fluctuations in voltage and frequency of power supply can cause noticeable variations in blower output.

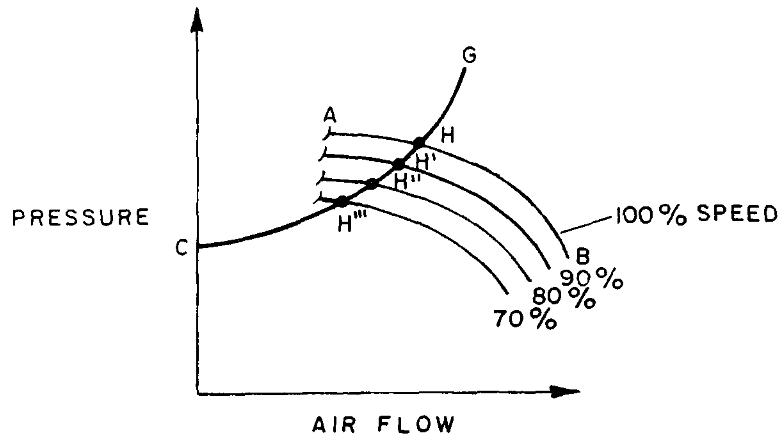


Figure 25. Blower speed control.

Inlet throttling--The most versatile method of controlling blower output over wide ranges of back pressure and flow is to vary the throttling effect of guide-vanes installed on the inlet side of the blower.

The effects of varying inlet guide-vane angles on output of a typical centrifugal blower are illustrated in Figure 26. This method of control allows blower output to be controlled over a much wider range (30 to 110 percent of rated capacity) without danger of incurring surge. Two points are worth noting in Figure 26. The first is that blower output can be varied over a wide range, even with discharge pressure held constant. The second is that "negative" angle of guide-vane throttling allows an increase of blower output above rated capacity.

The apparent contradiction shown by the second point--that increased (negative angle) throttling produces greater blower output--is explained by the fact that negative throttling angles introduce a helpful "preswirl" into the air stream just before it enters the impeller eye (positive throttling angles introduce a swirl that is opposite in direction to that of impeller rotation, thus reducing output). It should be understood, however, that although negative vane angle throttling allows blower output to be increased above rated capacity, this is not without an increase in power consumption.

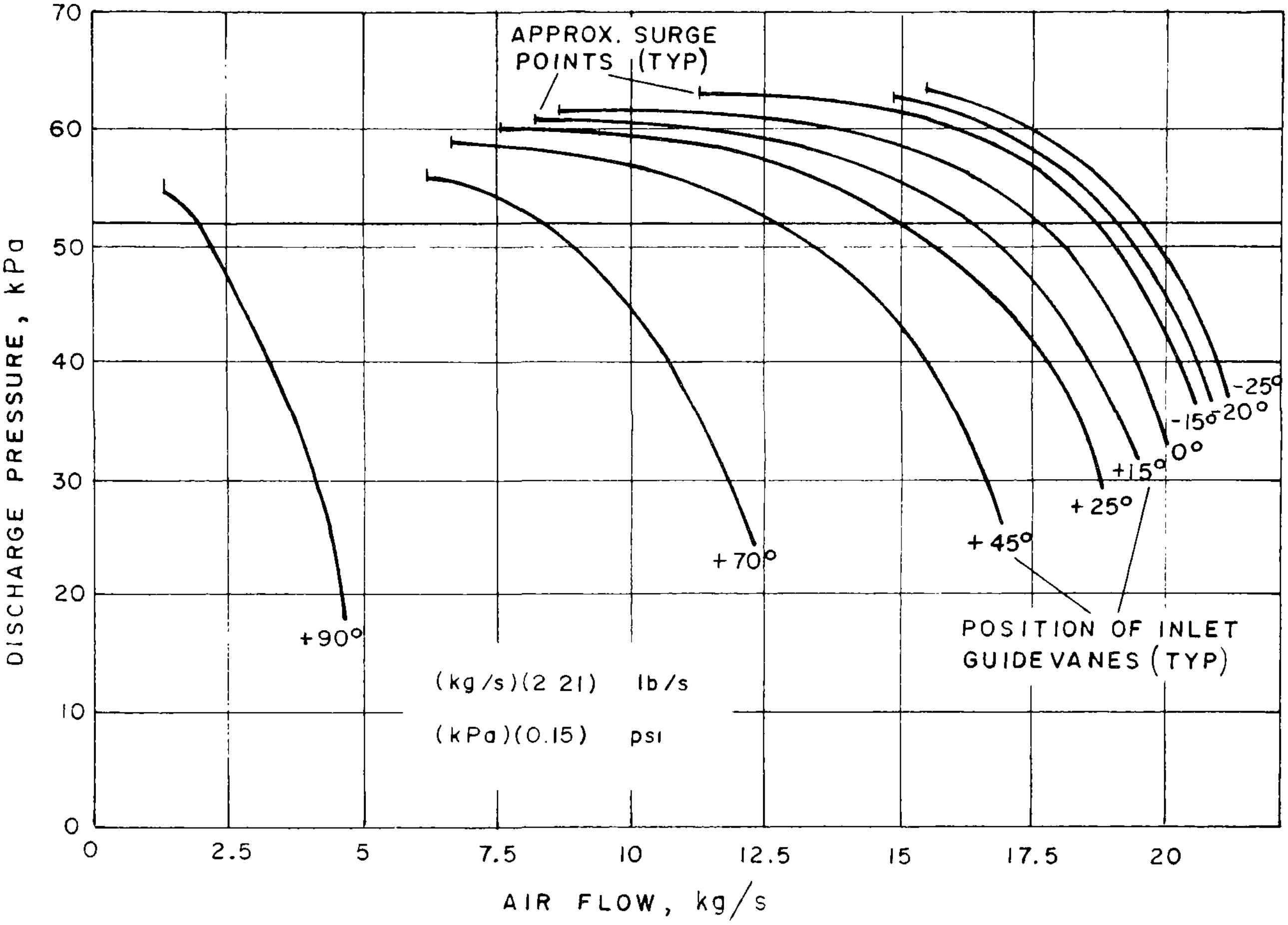


Figure 26. Inlet guidevane control for centrifugal blower.

Axial Blowers--

A multistage axial blower has two or more rows of rotating vanes operating in series on a single rotor and in a single casing. The casing includes stationary vanes that direct the gas to each succeeding row of rotating vanes. As the name implies, air flows through the blower axially. When the blower is operating, kinetic energy is converted to static energy; hence, during stable operation, the volume of air handled by the blower at a given speed is nearly constant, regardless of the discharge pressure. A typical pressure-output curve for axial blowers is shown in Figure 27. As indicated from the steepness of the curve, means must be provided for controlling compressor output. Three methods normally used are as follows:

Constant speed with throttled suction--A butterfly valve in the suction line is position-regulated to control the compressor output.

Constant speed with movable inlet vanes--For large blowers, handling air or clean gas, regulation is accomplished by a "prerotation" device

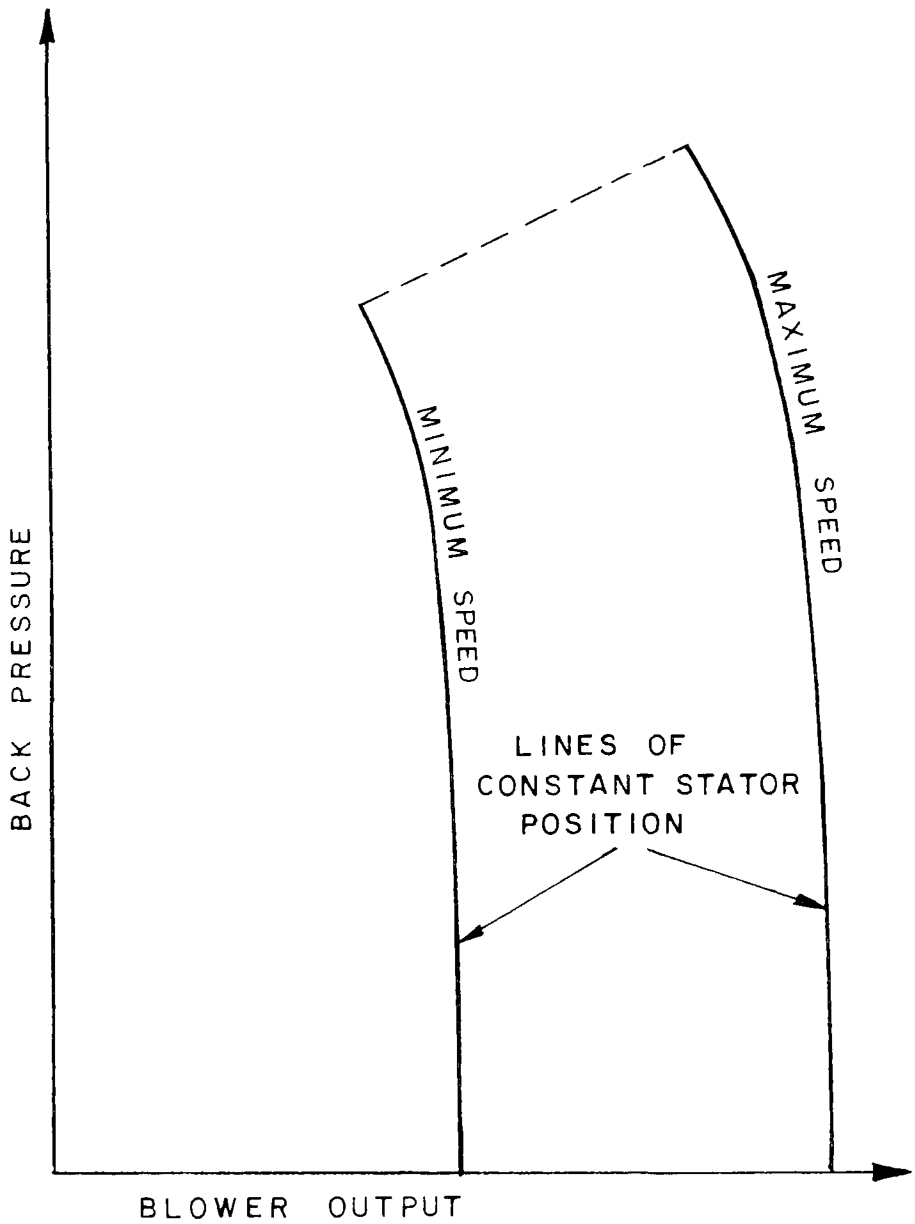


Figure 27. Axial blower characteristic curve.

consisting essentially of a system of movable vanes at the eye of the compressor impellers. By moving these vanes, the flow of air at the impeller eye is directed toward the direction of rotation, which has the effect of reducing the pressure rise through the impeller without the losses accompanying throttling of the inlet.

Variable speed drive--The range of speed adjustment depends upon the characteristics of the drive unit.

Surge Control of Dynamic Blowers--

All dynamic blowers (machines in which gas is compressed by the mechanical action of rotating vanes or impellers imparting velocity and pressure to the flowing medium (29)) have a minimum flow point below which performance is unstable. If the output of a dynamic blower is decreased to a minimum point, a condition is reached where two flow rates can be associated with the same pressure, thereby causing instability. This instability or surge limit comprises pulsations in pressure and flow which may cause compressor damage. The surge limit is affected by (a) type of compressor, (b) design pressure ratio, (c) characteristics of the gas handled, and (d) speed.

Surge is prevented by maintaining a flow greater than the safe minimum. This can be accomplished by blowing off or recycling excess flow by automatically opening a bypass or recirculation valve. Figures 28 and 29 represent typical performance characteristic curves for an axial and centrifugal blower, respectively. These curves demonstrate that, at a given speed, an axial blower approximates a constant volume, variable pressure characteristic, while a centrifugal blower approximates a constant pressure, variable volume characteristic. Thus, axial blower antisurge control should be pressure oriented, while centrifugal blower surge control should be flow oriented (29).

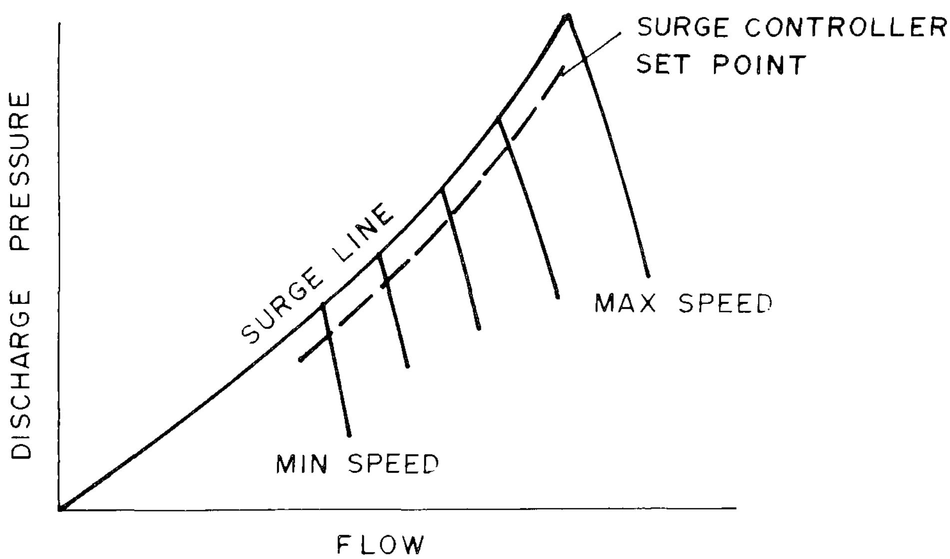


Figure 28. Typical performance characteristic curve for an axial blower with variable speed control (29).

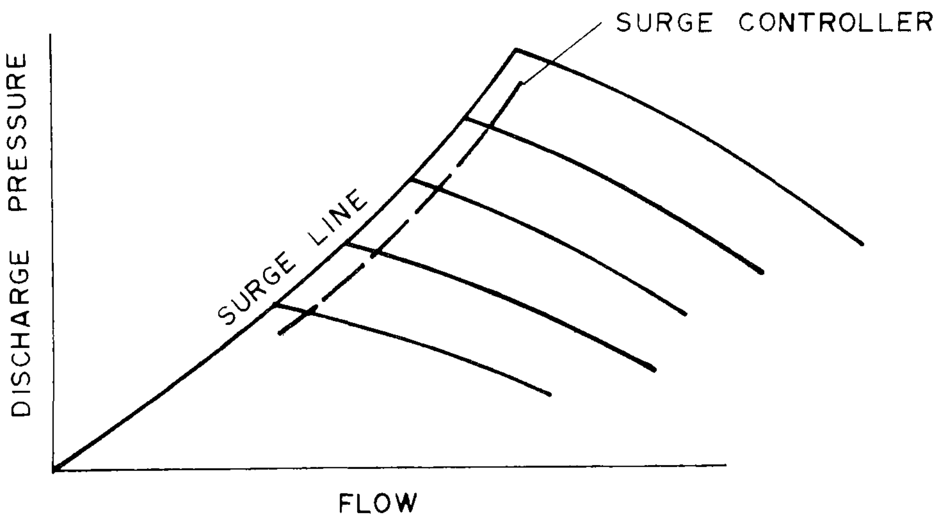


Figure 29. Typical performance characteristic curve for a centrifugal blower with variable speed control (29).

A surge controller is employed in surge control systems to limit the discharge pressure of axial blowers and maintain a minimum flow for centrifugal blowers. The surge controller compares the values of two sides of an equation which defines the surge limit condition. If the equation is unbalanced in the "safe" direction, the controller keeps the bypass valve closed. If the equation approaches balance, i.e., the surge line, the controller must start to open the bypass valve and also prevent the equation from becoming unbalanced in the surge direction. The controller throttles the bypass valve to various positions to maintain the system slightly on the safe side of surge. An auxiliary device lets the controller catch the system without a temporary overshoot in surge conditions, despite the presence of the integral control mode. This overshoot or anticontroller wind-up feature must always be used with the surge controller and is readily available from all instrument manufacturers in both pneumatic and electronic models.

The surge line equation depends on actual blower characteristics and is quite different for variable speed operation than for inlet throttling. The surge controller must keep the blower from operating to the left of the surge line, shown in Figures 28 and 29, regardless of speed, flow, pressure, and inlet gas temperature. The surge line is parabolic when plotted on a graph of discharge pressure versus volumetric flow. At constant gas specific gravity, the surge line is defined by equation (7), taken from Reference 5:

$$\left[f(T)\right]\left[DP\right] = KH_1 \tag{7}$$

where $f(T)$ = a computed function of the inlet gas temperature

DP = the differential pressure across the blower

H_1 = the flowmeter differential

K = a constant

Rather than trying to calculate the surge line theoretically, it is much more satisfactory to obtain the actual performance test curves from the manufacturer after he has tested the blower. Often, many simplifications can be made in the instrumentation system to obtain a good approximation to the surge line.

Typical pressure oriented surge control systems for suction throttled and variable speed blowers are shown in Figures 30 and 31. In Figure 30, surge controller PIC maintains the discharge pressure below a set point by opening the relief valve as required. The surge controller set point is modified by a signal from the inlet pressure transmitter, PT1 and temperature transmitter TT through characterizing relay FY. In Figure 31, surge controller PIC functions in a similar manner as in Figure 30, with the exception that the controller set point is modified by speed transmitter ST as well as suction temperature and pressure.

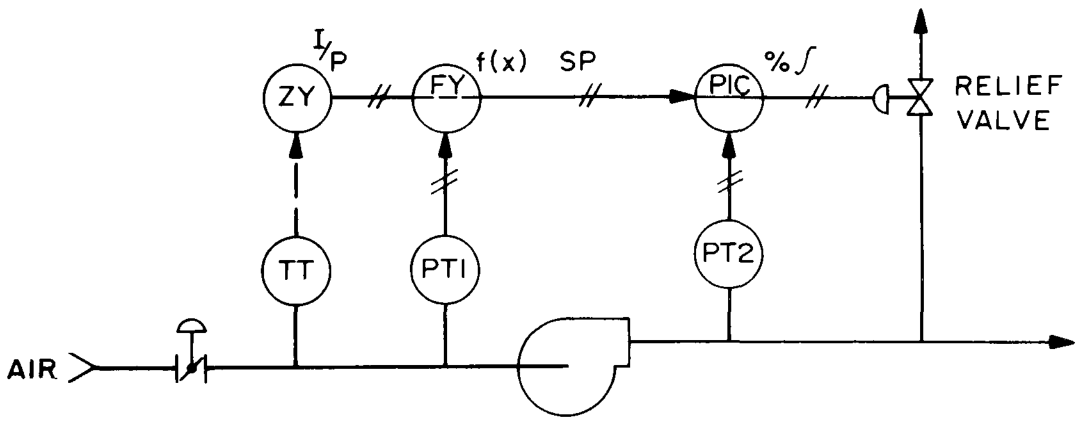


Figure 30. Pressure oriented surge control system for suction throttled blower (29).

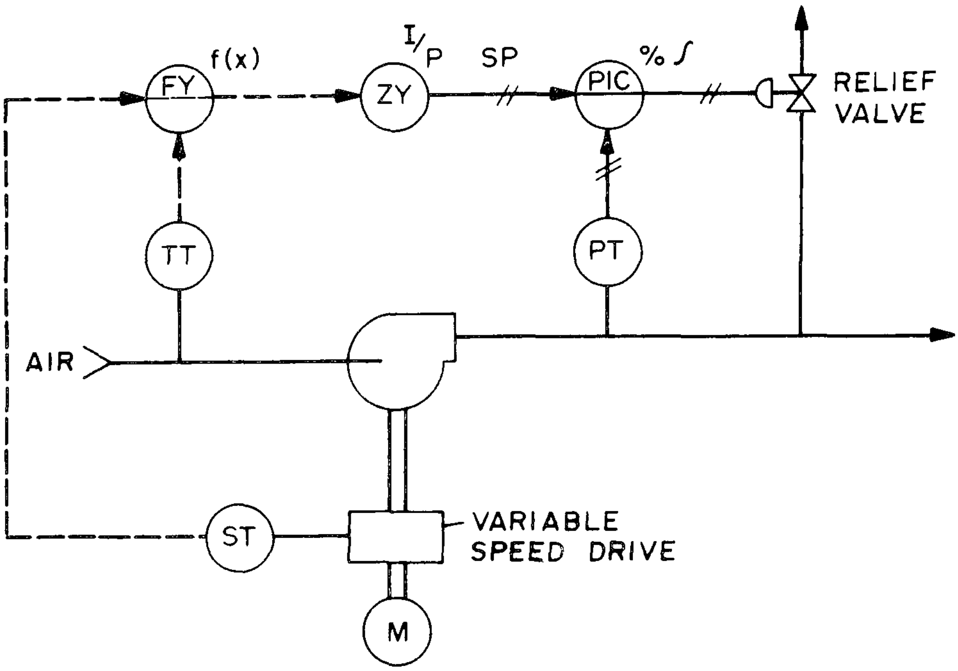


Figure 31. Pressure oriented surge control system for variable speed blower (29).

Figure 32 shows a basic flow oriented surge control system suitable for a centrifugal blower. Referring to Figure 29, surge controller FIC will maintain the discharge flow above the set point (dotted line) by opening the relief valve as required. No set point modification with speed is required with discharge flow monitoring since the flow element differential pressure remains essentially constant for speed variations.

Various surge control system arrangements result in different operating ranges available to the compressor. Figure 33 illustrates a surge control system that maximizes the operating range for a suction throttled compressor. Surge controller UIC maintains a minimum DP/P_2, where DP is the differential pressure across the flow element and P_2 is the discharge pressure. Relay FY computes the ratio of DP/P_2 and the result is fed to surge controller UIC. Since a constant value of DP/P_2 can be maintained that matches the surge line, maximum compressor operating range is available. In practice, the set point is set just to the right of the surge line as shown in Figure 33 (29).

Mechanical Aeration

Mechanical aerators have gained wide acceptance in the wastewater treatment industry in the past ten years. They fall into five broad categories: plate, updraft, downdraft, combination and brush type.

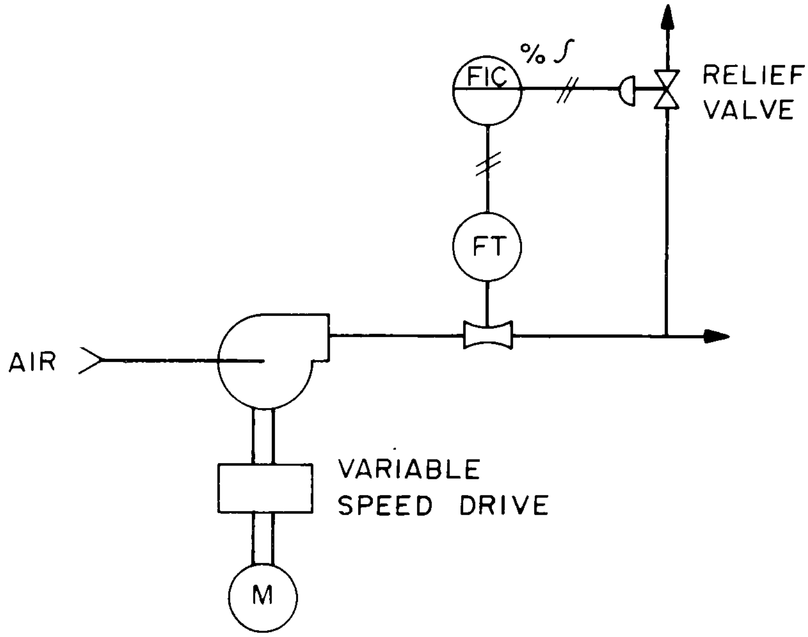


Figure 32. Flow oriented surge control system for variable speed blower (29).

Plate Type--

The plate type aerator (Figure 34) employs a circular plate equipped with radial blades and creates a large amount of turbulence by causing a peripheral hydraulic jump. Air is entrained in the mixed liquor by surface turbulence from the hydraulic jump and by air entrainment in a low pressure region behind the rotor blades. Normally only a surface turbine plate is provided, but for some applications a second rotor, located at midtank depth, is used.

Updraft Type--

The updraft type aerator (Figure 35) is perhaps the most popular of the mechanical aerators. It employs a surface impeller which draws liquid upward and violently outward at the surface. The surface turbulence effects oxygen transfer. Some updraft designs include draft tubes which direct liquid to the impeller more efficiently.

Downdraft Type--

The downdraft type aerator employs an impeller in a vertical tube to force liquid from the surface, down through the tube to the bottom of the tank. Air is entrained in the liquid as it is forced down into the tube.

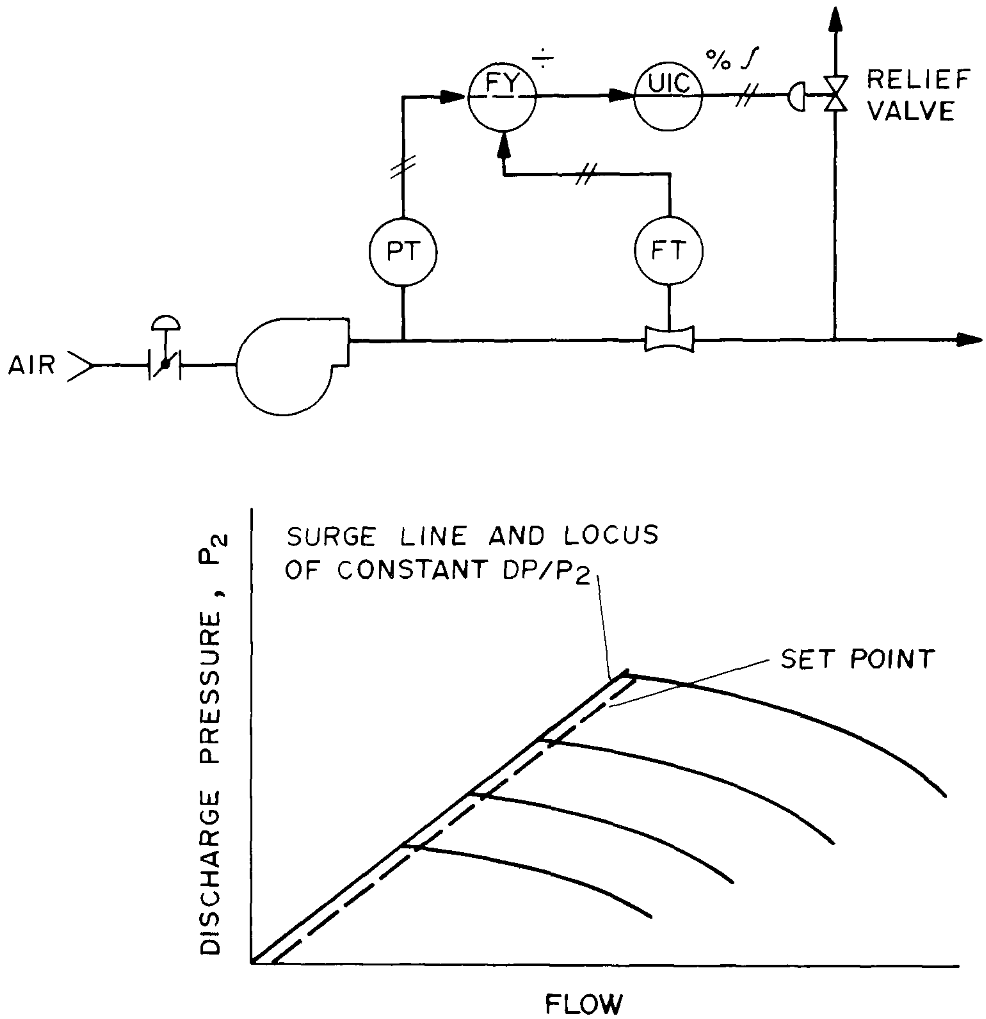


Figure 33. **Surge control system to maximize blower operating range (29).**

Combination Type--

The combination type aerator (Figure 36) employs both mechanical and diffused aeration. Usually, two impellers are provided; one at the surface and one near the tank bottom at the point of diffused air input. Air is introduced through a ring containing orifices and the turbine shears the bubbles into smaller sizes. The surface impeller provides a high degree of oxygen transfer by turbulent mixing.

Cage or Brush Type--

The cage or brush type aerator (Figure 37) rotates around a horizontal shaft equipped with a series of projections. Oxygen transfer is accomplished by surface turbulence. The brush type aerator is used extensively in oxidation ditch applications because, in addition to its good oxygen transfer characteristics, it is an excellent means of inducing circulation in channel-type aeration basins.

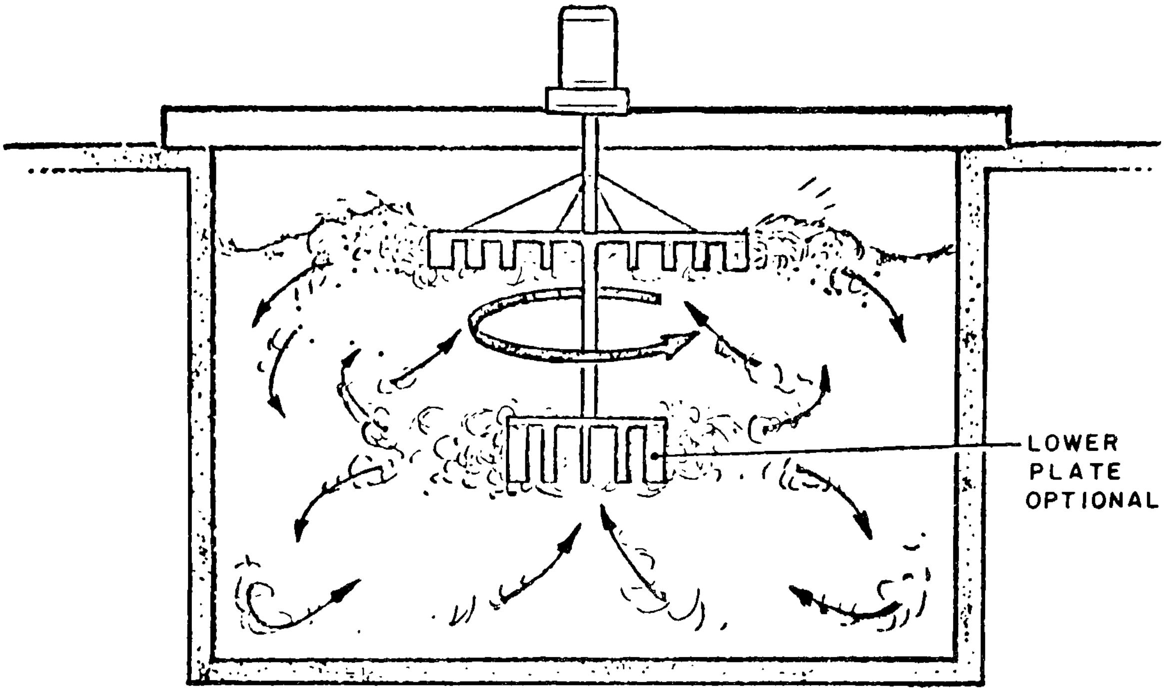


Figure 34. Plate type aerator (1).

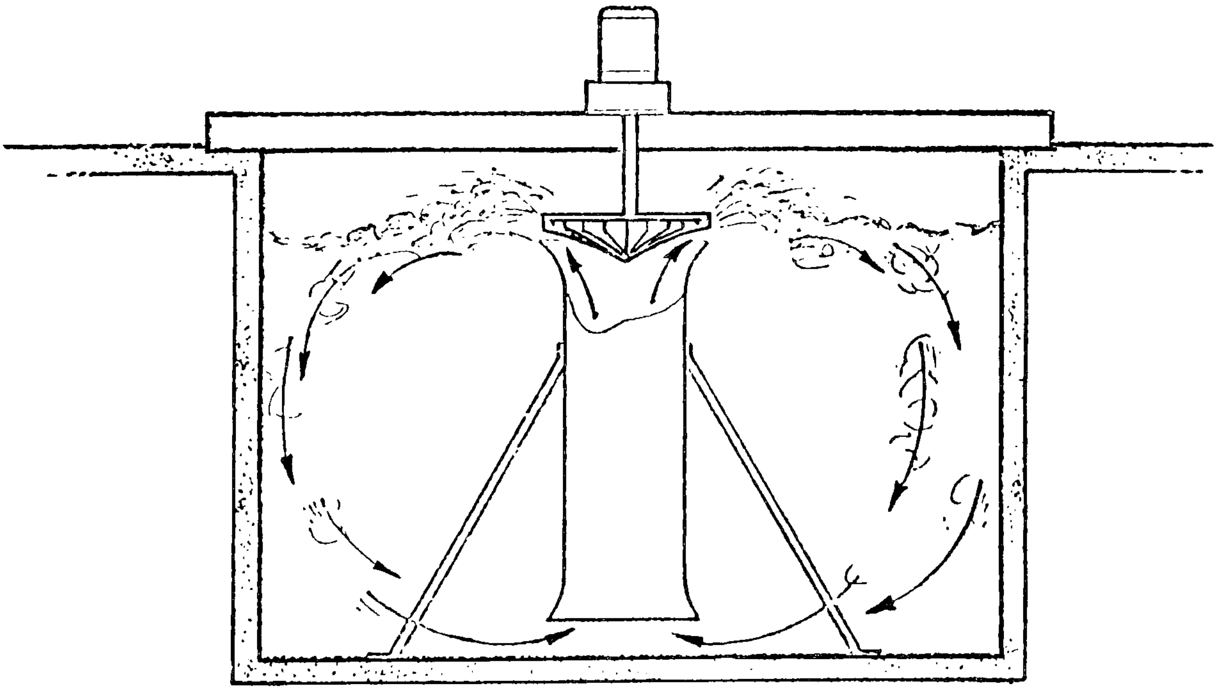


Figure 35. Updraft type aerator (1).

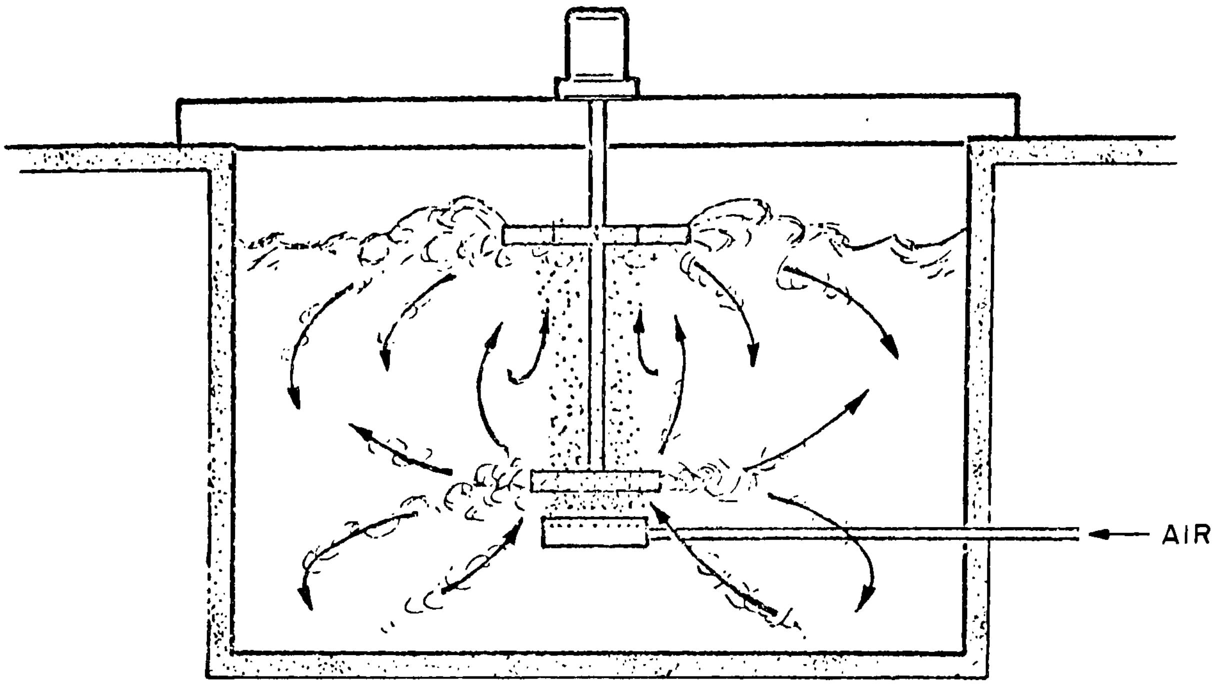


Figure 36. Combination type aerator (1).

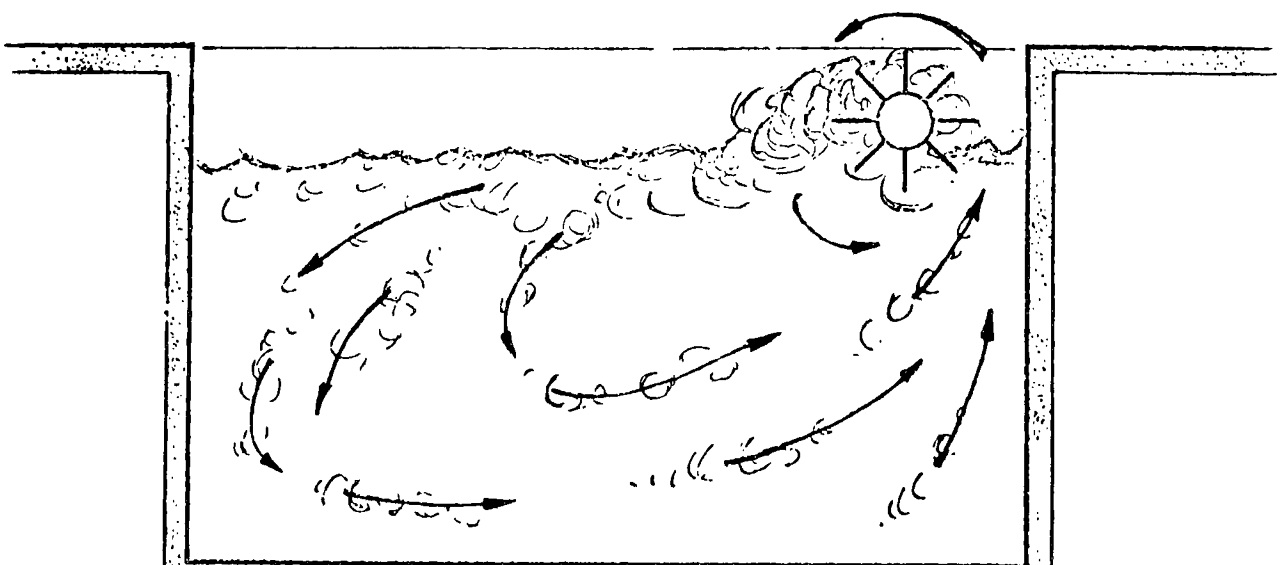


Figure 37. Brush type aerator (1).

The performance of all fixed mechanical aerators is affected by their submergence. Therefore, careful control of the oxidation tank water surface level is an important concern. Oxygen transfer efficiency decreases and power increases with increasing submergence. Some manufacturers have taken advantage of this characteristic to optimize aerator power consumption by means of an automatically adjustable outlet weir. In such systems, the height of the weir is varied to change the aerator submergence and hold the mixed liquor dissolved oxygen concentration at the desired level. This has not always been successful, however, as the aerator tends to "pump" the fluid over the weir, causing a nonuniform elevation in the tank. Additional information on types and applications of mechanical aerators can be found in Reference 2.

High Purity Oxygen

Oxygenation of mixed liquor with pure oxygen has been the subject of experimentation for about 20 years. Only recently, however, has an attempt been made to commercially market such a system. The Union Carbide Corporation and others have been engaged for several years investigating the use of pure oxygen aeration. The research has largely taken the form of pilot plant studies and has culminated in the development of patented processes such as the "Unox" (37) and "Marox" (FMC Corporation) systems. The major advantage of the Unox system over conventional air aeration systems is an ability to dissolve larger amounts of oxygen per unit volume of reactor.

Typically, the volume of oxygen used in the Unox system is only about 1-2 percent of the volume of air required by a comparable air aeration plant. Because that volume is insufficient to ensure mixing and prevent settling of solids, mechanical mixing must be employed. Oxygen dissolution systems are designed around surface, submerged turbine or combined mixers. Figure 38 shows a schematic cross section through a typical oxygen oxidation tank with a submerged turbine design. The tank is covered (usually with a concrete slab) and is divided into a number of stages by baffle walls. The liquid and gas flow concurrently through the tank, with the primary effluent, return sludge and oxygen being introduced together in the first stage. The oxygen is introduced at a gage pressure of 0.25-1.0 kPa (1-4 inches) of water column, and small recirculating gas compressors in each stage collect the gas above the liquid level and discharge it through the hollow shaft of a rotating sparger device, or through a separate pipe, at a rate sufficient to maintain the required dissolved oxygen concentration.

Gas is recirculated within each stage at varying rates to meet the decreasing oxygen demand as the mixed liquor progresses from stage to stage. The rate of gas flow within each stage is usually greater than the rate from stage to stage. Effluent mixed liquor from the system is settled in the conventional manner and sludge is returned to the oxidation tank.

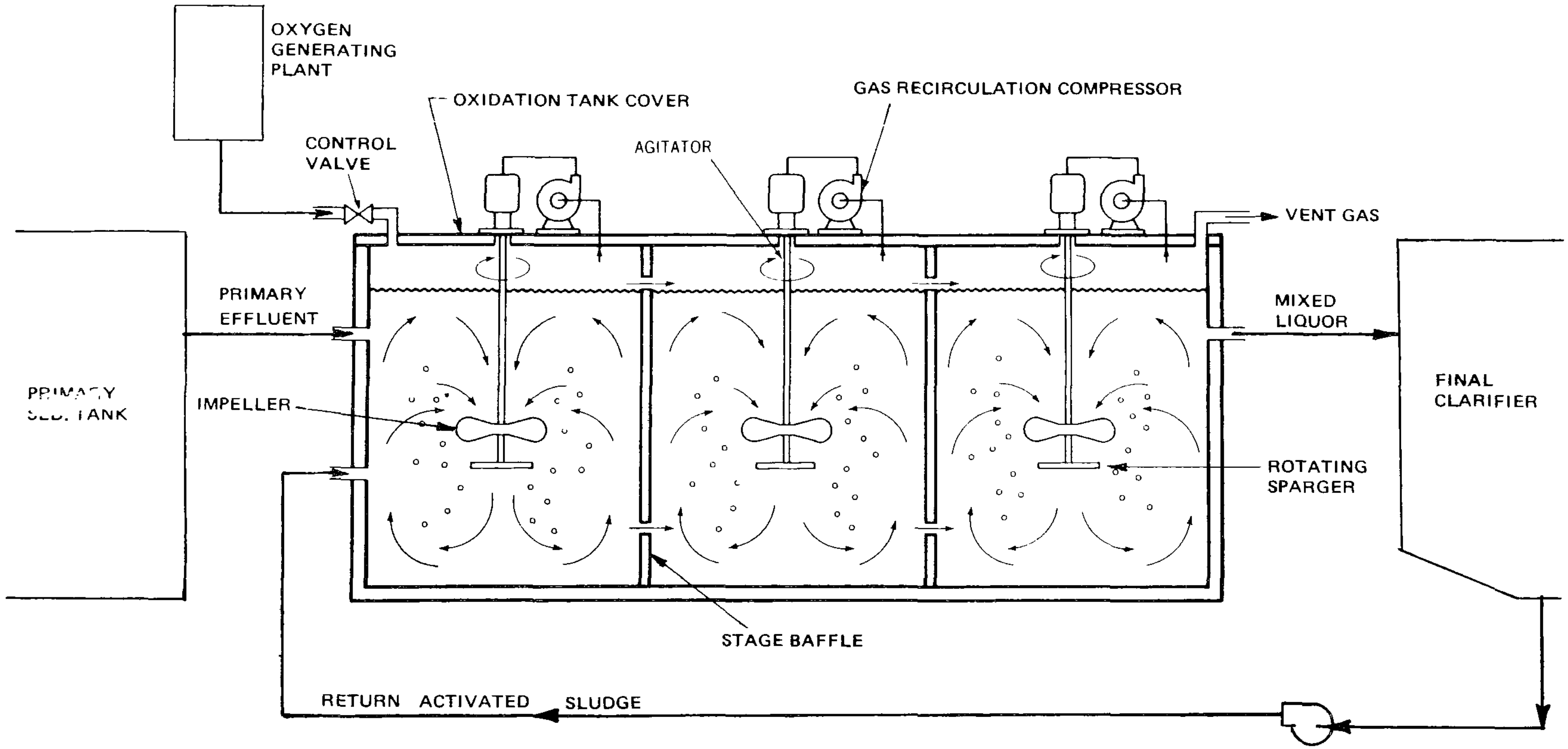


Figure 38. Submerged turbine mixer oxygen dissolution system.

The entire tank is fitted with a gastight cover to contain the oxygen gas. A restricted exhaust gas line from the final stage vents the waste gas to the atmosphere. Due to the net dissolution of gas, the amount of gas vented represents only 10 to 20 percent of the oxygen gas feed rate and the vented stream is about 50 percent oxygen.

Alternatively, the mass transfer and mixing in an oxygen dissolution system may be accomplished with surface aerators as shown in Figure 39. The surface aerators bring quantities of the wastewater to the surface for contact with the oxygen-rich atmosphere under the tank cover. Oxygen transfer occurs through direct contact as the wastewater is sprayed through the oxygen atmosphere and by entrainment as splashing liquid impinges into the bulk liquid. Lower impellers, as shown in Figure 39, are sometimes required for operation in deep basins.

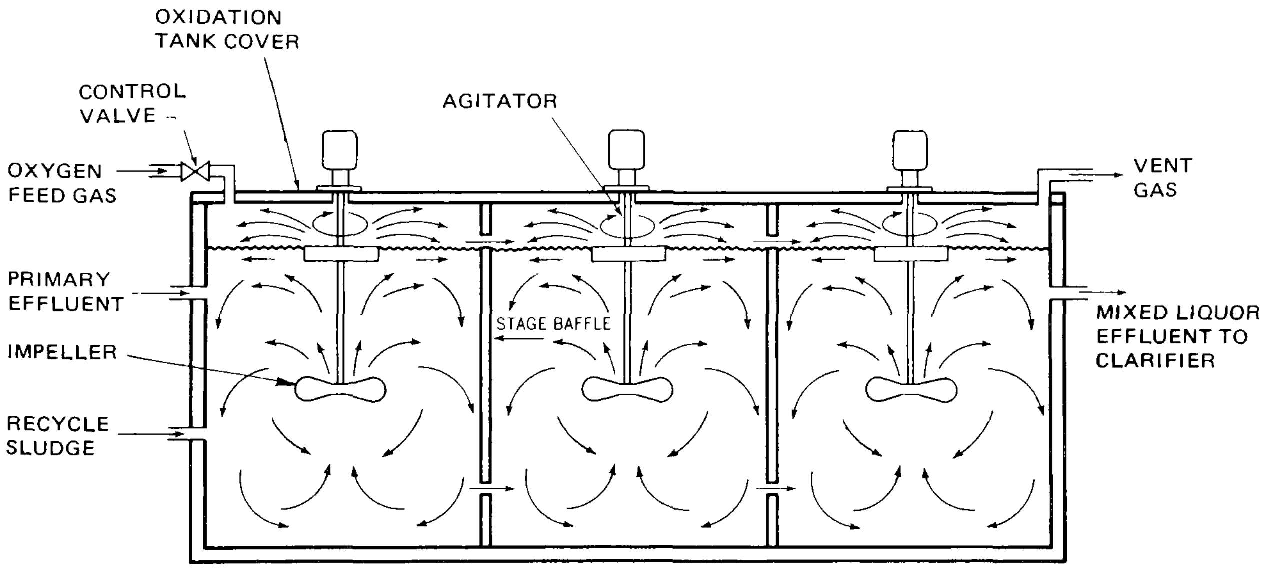


Figure 39. Surface mixer oxygen dissolution system.

Hybrid or combined surface and submerged turbine oxygen dissolution systems have been successfully used in a number of installations. For this design, a surface mixer is placed on a common shaft with a submerged turbine aerator. Flexibility is achieved through changes in mixer speed and gas flow rate.

Oxygen is usually supplied from an oxygen generating plant that forms an essential part of the treatment system. Two types of oxygen generating plants are offered: (a) a cryogenic air separation process for larger plants; and (b) a package type pressure-swing absorption (PSA) process for smaller plants.

Operation of oxygen aeration plants is characterized by:

1. High BOD loadings per unit volume of reactor.
2. High mixed liquor volatile suspended solids concentrations.
3. High dissolved oxygen concentrations (6 to 10 ppm).
4. Denser secondary sludge.
5. Low sludge yields.

Table 2 compares typical air aeration characteristics with those of seven pilot Unox installations (39). As indicated, detention time is 1/2 to 1/4 that in conventional plants. Short detention time, coupled with high mixed liquor solids concentration, results in smaller tanks, meaning less capital cost and less land area. On the other hand, larger secondary clarifiers are normally required to maintain the higher mixed liquor suspended solids levels in the oxygen system.

TABLE 2. COMPARISON OF UNOX OPERATING RESULTS WITH A TYPICAL CONVENTIONAL AIR AERATION PLANT (39)

Item	Typical air aeration plant	Unox Pilot Studies						
		I	II	III	IV	V	VI	VII
Aeration time, hrs (based on raw sewage flow)	4-8	1.5	2.0	1.8	1.7	1.8	1.8	2.2
MLVSS, ppm	1500-2500	7000	7000	5100	4000	5100	5500	5500
Loading, kg BOD_5/kg MLVSS/day	0.3-0.4	0.80	0.57	0.75	0.90	1.34	0.30	0.70
Loading, $mg/m^3/s$	4.6-15	39.5	26.9	33.4	35.2	68.6	17	40.8
RAS solids conc., percent solids	0.5-1.0	3.0	2.0	1.7	2.2	1.5	1.6	1.6
Raw sewage loadings								
BOD_5, ppm	150-300	220	195	215	200	440	115	340
SS, ppm	200-300	175	180	185	130	200	100	120
Final effluent characteristics								
BOD_5, ppm	10-25	22	10	22	20	22	12	34
SS, ppm	10-25	19	10	55	16	18	20	36
Sludge Volume Index	100-150	36	38	62	45	80	42	65
Solids production, kg/kg BOD_5 removed	0.5-0.75	.58	.70	.30	.75	.48	.39	.45

Note ($mg/m^3/s$)(5.39) lb/1000 cf/day

With its high oxygen transfer capabilities, the Unox system is able to operate at high MLSS concentrations. This enables the system to readily absorb shock organic and toxic loads, much as in a completely mixed activated sludge system (37).

The reasons for high solids in the oxygen system are not fully understood, although work to date indicates the primary causes are: (a) more fine particles in the oxygen plant sludge due to the higher process rates; and (b) the high MLSS in the oxygen plant being applied to conventionally sized final clarifiers. The latter reason is probably the most important of the two. The present lack of information on the reasons for poorer clarification point to the need for further research on this aspect of operation to develop more rational design criteria for final clarifiers.

Optimum nitrification takes place within a fairly narrow pH range of 7.0 to 9.0, with pH 8.5 being the ideal. In conventional plants which are nitrifying, the CO_2 produced by organic decomposition is continually stripped out of the mixed liquor by the aeration air. Maintenance of reasonable pH levels is, therefore, possible. In high purity oxygen systems utilizing closed tanks, such stripping is not possible, with the result that CO_2 builds up and the pH is lowered. In some of the Unox pilot studies, mixed liquor pH values as low as 6.0 have been reported. Nitrification reactions are severely retarded at such low pH, although recovery has been noted following acclimation (Haug, R. T. and McCarty, P. L., "The Effects of High Oxygen Tension and pH on Nitrification," unpublished paper, November, 1970). Research is being pursued to solve this problem with two possibilities under investigation. The most promising appears to be two-stage oxygenation with air stripping of CO_2 taking place in a channel connecting the two stages. The second method involves lime treatment of the raw sewage which not only raises pH, but results in higher removal of carbonaceous BOD in primary sedimentation tanks with a corresponding decrease in BOD load to the aeration system.

Comparison of Conventional Systems

The designer is faced with a difficult choice between mechanical and diffused aeration. Data can be produced to demonstrate the high oxygen transfer efficiency, the low power requirements, and the benefits to biological growth afforded by any particular system. Care must be exercised in evaluating such data; unless one knows the conditions under which tests were conducted, how calculations are made, and what factors have or have not been taken into account, he should not select system A over system B simply because system A claims a higher oxygen transfer efficiency. The major factors that should be evaluated are: (a) aerator oxygenation efficiency, (b) overall system economy, (c) mixing and effects on biological growths, and (d) flexibility of operation under the required range of loadings and modes of operation. Each of these factors is discussed below.

Aerator Oxygenation Efficiency--

Mechanical aerators are commonly rated in terms of pounds of oxygen transferred at standard conditions per brake hp hour. Diffusers are rated by their oxygen transfer efficiency expressed as a percentage of oxygen supplied. The two can be approximately compared by the values given in Table 3 (21).

TABLE 3. RELATION OF OXYGEN TRANSFER EFFICIENCY TO AERATOR POWER EFFICIENCY (37)

Diffuser oxygen transfer efficiency, per cent	Aerator power efficiency, kg O_2/kW/hr
4	0.75
6	1.12
8	1.49
10	1.87
12	2.25

Note (kg O_2/kW/hr)(1.65) = lb O_2/bhp/hr

Overall System Economy--

Economic comparison of two aeration methods must be made on the basis of overall system economy, taking into account all cost factors including capital recovery, preventive maintenance requirements, operational attendance, breakdown maintenance requirements, utilities and the like.

Mixing and Effects on Biological Growth--

The degree of mixing is affected by tank geometry, locations of inlets and outlets, and the type of aeration device employed. Either diffused aeration or mechanical aeration can achieve good mixing, providing the tank design is correct. The belief persists, however, that mechanical aerators are superior to diffusers from the standpoint of mixing.

On the other hand, many engineers believe that the turbulent environment in a mechanical aeration plant is not conducive to balanced biological growth. In a study recently conducted at a medium sized plant in England, where half the flow goes to a diffused air plant employing fine bubble, dome-type diffusers, and the other half goes to a mechanical aeration plant, researchers identified ten types of organisms in the mechanical aeration basins while more than 60 were found in the diffused aeration tanks. The difference was attributed to the high degree of turbulence in the mechanical aeration basins causing floc breakup and discouraging growth of the more fragile types of protozoa. The ten organisms identified in the mechanical aeration basins were all of the hardy, stalked, ciliate type.

Other researchers have reported that the settling characteristics of sludge from diffused air plants are superior to those from mechanical aeration plants. This phenomenom is also attributed to the breakup of activated sludge floc caused by the violent turbulence associated with mechanical aeration (22,23,24). However, further work needs to be completed to define the effects of different aeration methods upon mixing and biological growth.

Flexibility of Operation--

Flexibility of operation implies the ability of the aeration method to efficiently cope with the entire range of loads and operational modes encountered in normal operation. For example, tapered aeration is more easily achieved with a diffused air system than with mechanical aerators. Where a high degree of nitrification is required, diffused air is again the better choice because such a system can more easily and economically cope with the large daily variations in ammonia concentration which are experienced in most plants.

Of the available aeration devices, mechanical surface aerators are least well suited to nitrification applications because they are normally designed to operate at fixed speed and, therefore, must overaerate most of the day to satisfy peak oxygen demands. Even when designed for variable blade submergence, the units are limited to matching less than a 2:1 variation in load. When variable submergence is coupled with a two-speed drive, less than a 3:1 load variation can be matched. Therefore, unless flow equalization is provided somewhere in the system, mechanical surface aerators cannot match variations in nitrogen loads without overaerating the mixed liquor during a significant portion of the day.

Diffused air aeration presents a different picture. Air rates can be easily modulated to closely match the load by turning down or shutting off individual blowers. Thus, the diurnal load variations can be matched without the necessity of overaerating the mixed liquor and wasting power. Fine bubble diffusers can be arranged across the tank floor, allowing fairly even distribution of energy input. Gentler mixing is provided than with mechanical aeration plants, providing less tendency for floc breakup.

Submerged turbine aeration systems are intermediate in terms of their responsiveness to the problem of aeration in nitrification systems. Because of their capability to vary the air rate to the sparger, they may be designed to match the load variation in oxygen demand. A drawback, however, is that the impeller normally operates at fixed speed, imparting no turndown capability for a significant part of the power draw.

Comparison of oxygenation capacity of various devices is possible on a quantitative basis. Comparison of other aspects of operation, particularly those related to mixing and the effects on biological growth, is difficult, if not impossible, because of the subjective nature of such comparisons. Each case must therefore be decided upon its own merits. In some cases, diffused air will be an obvious choice, whereas in others, mechanical aeration may be appropriately selected. As a guide, the broad advantages and disadvantages of the various types of aeration devices are summarized in Table 4 (1).

TABLE 4. SUMMARY OF AERATOR CHARACTERISTICS RELATED TO ACTIVATED SLUDGE AERATION

Aerator Type	Advantages	Disadvantages	Best Use
Coarse bubble diffuser	Low capital cost Non clogging; air filtration not required Low maintenance cost Flexibility in operation - can put air where load is. Turbulent mixing Central blower station possible	Low oxygen transfer efficiency Turbulence promotes floc breakup.	Small municipal waste treatment plants and areas where dirty air creates filtration difficulties
Fine bubble diffuser	High oxygen efficiency Flexibility in operation- can put air where load is. Flexibility in tank design Good mixing Central blower station possible Gentle stirring promotes floc formation	Diffuser clogging; requires high degree of air filtration High capital cost Not suitable for completely mixed systems	Large municipal plants. Plants requiring low effluent BOD. Plants requiring high degree of nitrification.
Mechanical aerators - Updraft and Turbine Types	Low capital cost High oxygen transfer efficiency Good mixing	Multiple units require large number of operating drives and high maintenance and operation cost Insufficient oxygenation capacity for nitrification Icing problems in cold climates Turbulence promotes floc breakup Circulation patterns produce uneven D.O. distribution Water level control critical	Small plants where nitrification is not required Warm climates.
Mechanical aerators - Combination Type	Good mixing Moderate oxygen transfer efficiency High oxygen input capacity Wide oxygen input range	Requires both mechanical drives and central compressor station High capital cost High maintenance cost Turbulence promotes floc breakup	Plants with wide range of oxygenation requirements (trade wastes) Nitrification tanks
Mechanical aerators - Brush Type	High oxygen transfer efficiency Low capital cost Low maintenance cost	Restrictive tank design flexibility Icing Problems in cold climates Water level control critical Insufficient oxygenation capacity for nitrification Turbulence promotes floc breakup	Oxidation ditches

SECTION 6

DESIGN OF DISSOLVED OXYGEN CONTROL SYSTEMS

Control of air and oxygen dissolution in the mixed liquor is an important parameter in the activated sludge process. The desired strategy is to add sufficient air or oxygen to meet the time-varying oxygen demand of the mixed liquor. Because electrical energy is one of the major operating costs of the activated sludge process, there is an economic incentive to minimize unnecessary oxygenation.

If the DO level drops below approximately 0.5 ppm, oxygen becomes rate limiting and the aerobic bacteria become inactive. On the other hand, a DO level that is too high represents wasted power and, according to Ryder (32), can cause sludge bulking. Nitrification rates are limited at DO levels of less than 2.0 ppm; thus, DO control should be provided when nitrification is desired.

At the present time, DO is manually controlled in most activated sludge processes. The operator may attempt to pace oxygen transfer in proportion to the oxygen demand, but to ensure adequate oxygenation, the operator generally maintains an excess level of oxygen. In doing so, he usually provides more aeration than is required. Power costs for oxygenation can be minimized if oxygen transfer capacity is automatically paced in proportion to the time-varying oxygen demand.

Most existing activated sludge plants use air as an oxygen source. The preferred method of air flow control is to maintain the minimum DO level in each oxidation tank or tank pass that is necessary for adequate oxygenation. In the recently developed high purity oxygen process, the oxidation tanks are covered and, thus, function as on-line respirometers. Oxygen is supplied to the first stage of each oxidation tank in proportion to the oxygen uptake rate, as reflected by changes in oxidation tank gas pressure, and is exhausted as vent gas from the last stage of each tank. The oxygen purity control system maintains constant gas purity in the gas venting from each oxidation tank by modulation of the vent gas valve. The system is usually designed to consume 90 percent of the oxygen supplied. However, the pure oxygen systems do not directly provide DO control of the mixed liquor in the oxidation tanks.

PROCESS CONTROL FUNDAMENTALS

There are many ways of implementing control from a hardware viewpoint, including mechanical, pneumatic, electrical, electronic, analog and digital techniques. However, regardless of the mechanism used, the basic theory remains the same.

There are two basic types of control: open-loop and closed-loop. The two main forms of closed-loop control are feedback and feedforward. A brief description of each control type is given below.

Open-Loop Control

Figure 40 represents a typical open-loop control system. Open-loop control involves making an estimate of the form or quantity of action necessary to accomplish a desired objective. No check is made to determine whether or not the corrective action taken has accomplished the desired objective. In Figure 40, the fixed program is a time-related estimate of the amount of air required to satisfy the oxygen demand of the primary effluent over a 24-hour period.

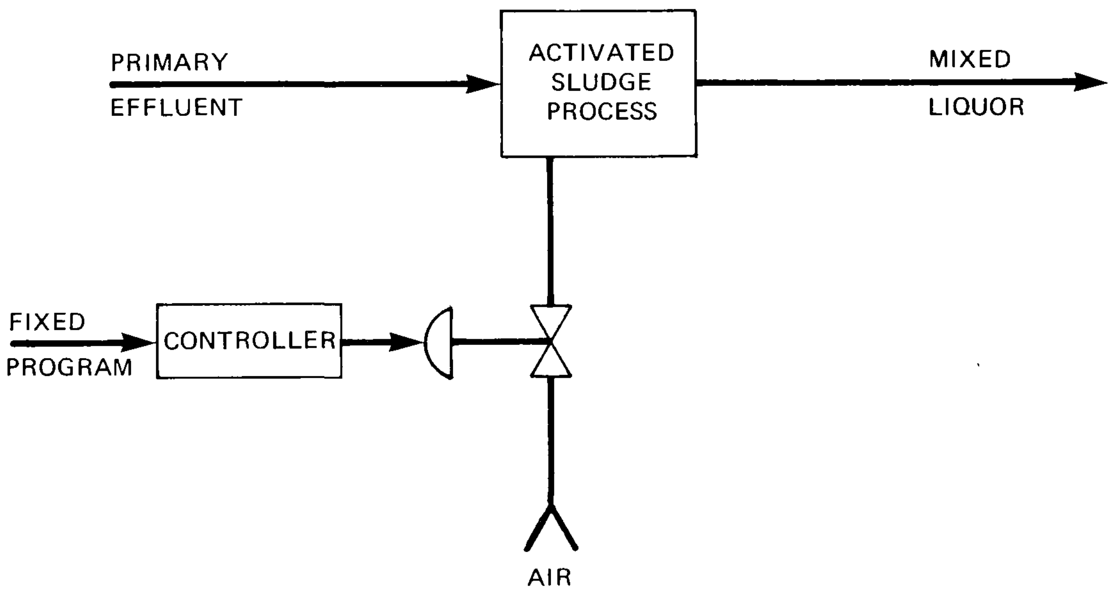


Figure 40. Open-loop control.

Closed-Loop Feedback Control

Figure 41 represents a typical closed-loop feedback control system. The controlled variable is the DO level in the mixed liquor. A measurement of the DO level is transmitted to an automatic controller, where it is compared with a set point or reference point. If a difference, or error, exists between the actual and desired DO level, the automatic controller adjusts the position of the air control valve, thereby modifying the effect of the manipulated variable (air) on the controlled variable (DO) and eliminating the error between the actual and desired DO level.

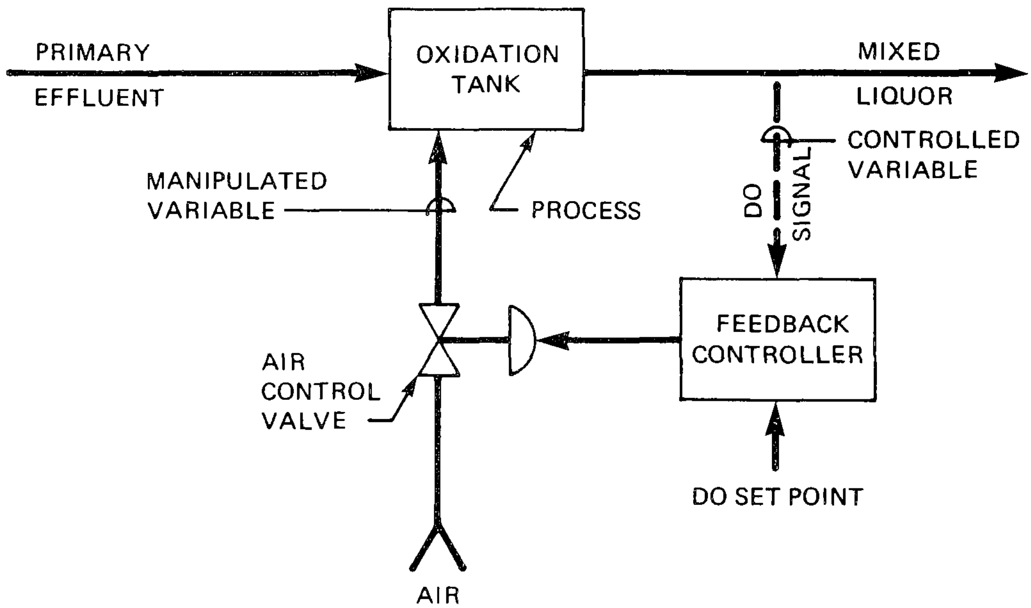


Figure 41. Closed-loop feedback control.

Closed-Loop Feedforward Control

Figure 42 represents a typical closed-loop feedforward control system. One or more measurements related to the oxygen demand of the primary effluent, together with the DO set point, are used to compute the correct amount of air to meet the current oxygen demand of the process. Whenever a change in oxygen demand (disturbance) occurs, corrective action starts immediately to cancel the disturbance before it affects the controlled variable (DO level in mixed liquor). Feedforward control is theoretically capable of perfect control; its performance is only limited by the accuracy of the measurements and computations.

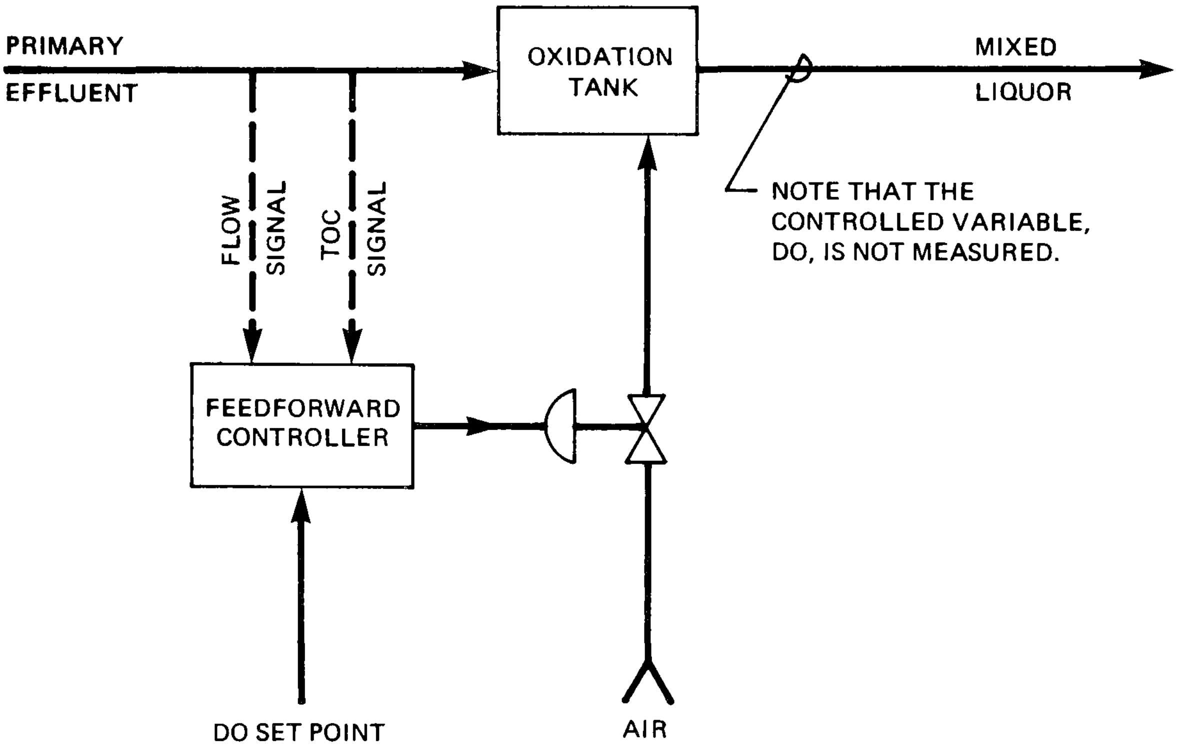


Figure 42. Closed-loop feedforward control.

The essential feature of feedforward control is the forward flow of information. The controlled variable is not used by the system, because this would constitute feedback; this point is important, because it shows how it is possible to control a variable influent with a continuous measurement of it available. A set point is essential, however, because any control system needs a "command" to give it direction.

Feedforward-Feedback Control

The only serious failing of feedforward control is its dependency on accuracy. To provide perfect control, a system must model the plant exactly; otherwise, whatever error that may exist in positioning the manipulated variable causes offset. Therefore, if the controlled variable can be measured, as is the case in the feedforward-feedback control system shown in Figure 43, a feedback controller is coupled to the feedforward controller to compensate for any input changes that have not been taken into consideration in the feedforward model and for inaccuracies in the various transmitters and computing elements in the system. In general, the feedback controller is used to adjust

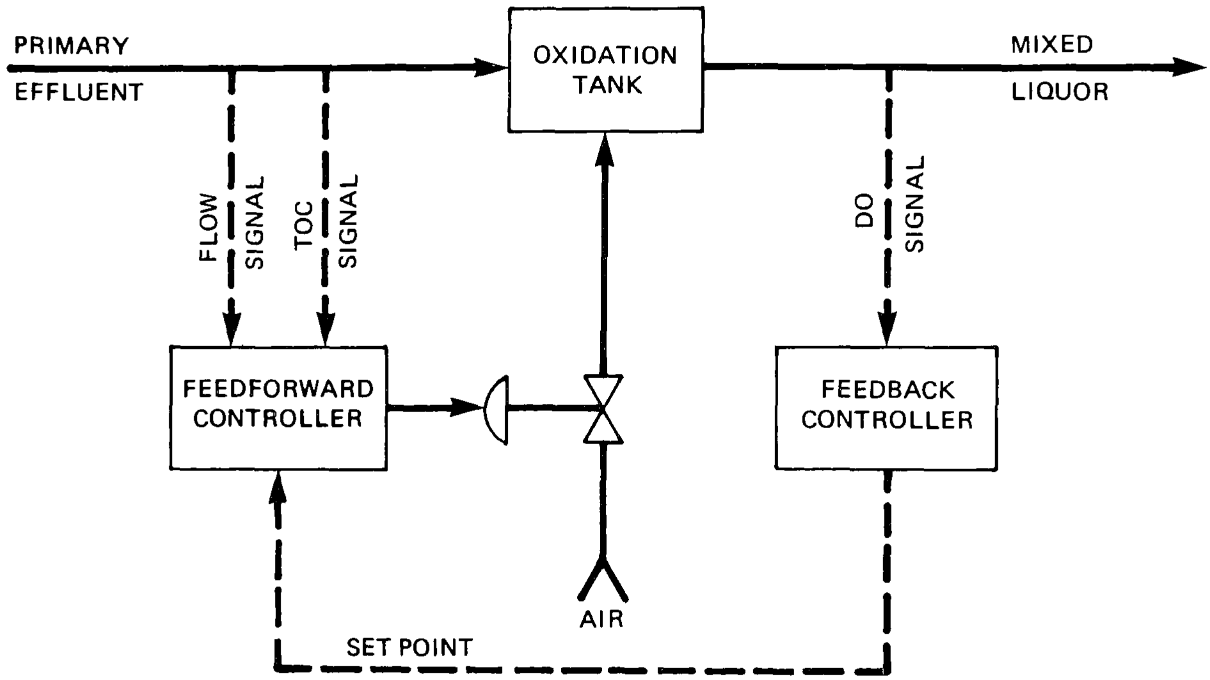


Figure 43. Feedforward-feedback control.

the set point of the feedforward controller. The difference between the set point and the output of the feedback controller is the offset, which would have appeared if feedback had not been used.

In feedforward-feedback control systems, the normal practice is to isolate all the deterministic or predictable factors and treat them insofar as is possible by feedforward control techniques. The use of feedback is reserved for the handling of random inputs and disturbances, where feed-forward techniques do not work. This arrangement reduces the gain and bandwidth requirements on the feedback loop(s) to a minimum and, therefore, minimizes stability problems and improves the performance of the feedback loop(s).

DISSOLVED OXYGEN MEASUREMENT TECHNIQUES

Basically, there are two direct and two indirect methods of continuously measuring dissolved oxygen. The two direct methods are (a) in-situ dissolved oxygen measurement using electrochemical sensors and (b) gas pressure and vent gas purity regulation in a closed oxidation tank employing pure oxygen for oxygenation of the mixed liquor. The two indirect methods are (a) influent flow and (b) oxidation-reduction potential (ORP) of the mixed liquor. Each of the four methods for the continuous measurement or computation of the dissolved oxygen of mixed liquor is described below.

Electrochemical Dissolved Oxygen Sensors

Dissolved oxygen sensors of the electrochemical type are suitable for continuous, in situ, DO measurement. All electrochemical DO sensors are affected by temperature, velocity, ionic strength and other environmental factors. Currently, three types of DO sensors are commercially available, and they operate on the following principles:

° A galvanic sensor in which molecular oxygen diffuses through a membrane and reacts with a lead/silver electrode system to produce a current proportional to the DO concentration.

° A polarographic cell that requires oxygen to diffuse through a membrane (typically Teflon) and be reduced by a polarizing voltage across metal electrodes of different nobility. This cell produces a current proportional to the DO concentration.

° A thallium cell in which oxygen reacts with thallium metal, producing thallous ions in proportion to the DO concentration. The potential developed is a function of thallous ions at the surface of the electrode but needs no membrane. However, caution should be exercised in the use of this electrode since thallium is injurious to health.

Membraned probes have been developed to avoid the problems encountered when electrodes contact the sample. For example, the membrane excludes most materials that could cause an erroneous output since they cannot diffuse through it. Electrolyte strength is also preserved since it is isolated from the sample by the membrane.

Oxygen Uptake Rate in a Closed Oxidation Tank

When a closed oxidation tank is used in the oxygen activated sludge process, it is possible to determine oxygen uptake of the mixed liquor in a given oxidation tank from the oxygen purity of the gas being vented from the oxidation tank. An increase in the oxygen uptake causes a reduction in the oxygen purity by opening the vent gas valve which causes a drop in oxidation tank gas pressure, which, in turn, causes additional oxygen to be added to the oxidation tank to restore the gas pressure to the desired level. Thus, oxygen is added to match the time-varying oxygen demand of the mixed liquor.

Influent Wastewater Flow as a Dissolved Oxygen Control Parameter

An indirect method for DO control in the activated sludge process is based upon maintaining a constant ratio between influent wastewater flow and air flow. In ratioing air to mixed liquor in the oxidation tank, it is customary to maintain the ratio at 4-11 cubic metres of free air per cubic metre (0.5-1.5 scfm/gallon) of wastewater treated. Present practice in many treatment plants involves manual adjustment of air feed to maintain the desired ratio. Since the wastewater flow through a treatment plant will undergo large fluctuations in the course of a 24-hour day, considerable plant operator attention must be devoted to maintaining proper air/wastewater flow ratios.

In plants where 24-hour supervision is impossible, operating procedure usually consists of increasing the air flow in the morning and decreasing it at night. Under such an operational procedure, changes in wastewater flow will result in either over or underaeration, accompanied by improper treatment. The main disadvantage of flow ratio control is that the oxygen demand per unit volume of fluid varies considerably in wastewater. Consequently, it is recommended that DO control systems based on influent wastewater flow be utilized only for wastewaters with a relatively uniform diurnal oxygen demand.

Oxidation-Reduction Potential as a Dissolved Oxygen Control Parameter

Oxidation-reduction potential (ORP) is the potential between the oxidants and reductants in a system without regard for the total quantity of either constituent or their biological activity. Biological activity considerations are important since inert oxidized salts may be recorded as oxidants, although their effect on biological reactions will be minimal. Therefore, a high ORP can develop even though the biological reaction is predominantly reductive in nature. Although it may be possible to correlate the ORP of any given mixed liquor to its oxygen demand, it is not possible to correlate the ORP's of mixed liquors in different treatment plants.

INSTALLATION, APPLICATION AND CALIBRATION OF DISSOLVED OXYGEN PROBES

All of the control systems described in this paper for diffused air and mechanical aeration systems employ, in situ, electrochemical dissolved oxygen (DO) probes for the measurement of mixed liquor DO levels. Accordingly, some guidelines concerning the application and installation of DO probes are given prior to discussing various aeration methods and associated DO control systems.

Installation and Application

The location points for DO probes will vary from plant to plant as well as for different operating configurations. Since it is difficult for the design engineer to predetermine the most suitable DO probe locations, any DO probe layout should be flexible enough to permit reconfiguration while the plant is operating. Multiple DO probe receptacles should be provided in each tank to permit probe relocation. Typical DO probe and receptacle locations for various process configurations are given in Figures 44 through 48.

For reliability, it is recommended that a DO analyzer/transmitter be provided for each DO probe that is employed for control purposes. However, for monitoring purposes, it is acceptable to use one analyzer and multiplex the outputs from two or more DO probes as shown in Figure 49.

DO probes are designed to be placed in sites where the transition time of the sample to the probe is essentially zero. However, if it is desired to locate the DO probe remote from the oxidation tank and pump a sample to the probe, the elapsed sample transfer time must be considered. In particular, if mixed liquor from an activated sludge process is to be transferred, the uptake rate of oxygen by the biological mass in the mixed liquor will decrease the DO level in the sample by the time it reaches the DO probe. For example assuming an uptake rate of 600 grams of oxygen per cubic metre per hour, the loss of oxygen would be 10 grams per cubic metre per minute. Thus, it can be seen that sample transfer should be rapid to minimize the change in DO concentration. However, sample transfer devices may cause reaeration. Consequently, unless the exact relationships are known, the value of sample and transport for DO measurements is questionable. It is recommended that DO probes be installed directly in the mixed liquor whenever possible.

Mounting

DO probe mounting requires careful consideration. The mounting structure must be sturdy enough to withstand continuous buffeting resulting from air agitation of the mixed liquor. In addition, the mounting assembly must permit easy removal of the probe assembly from the mixed liquor for routine maintenance and calibration. Figure 50 shows a typical installed dissolved oxygen probe assembly.

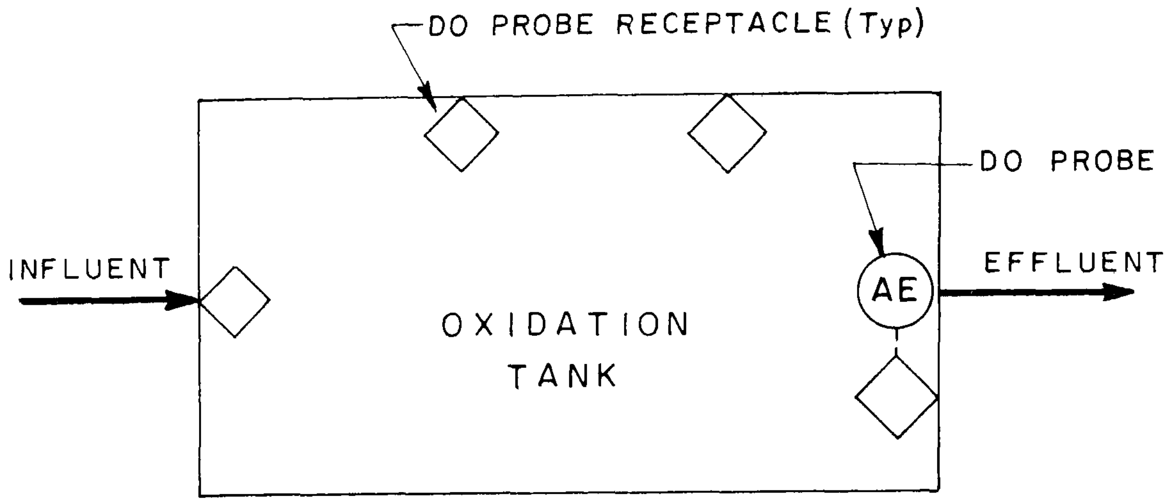


Figure 44. Plug flow, single pass oxidation tank - probe/receptacle locations.

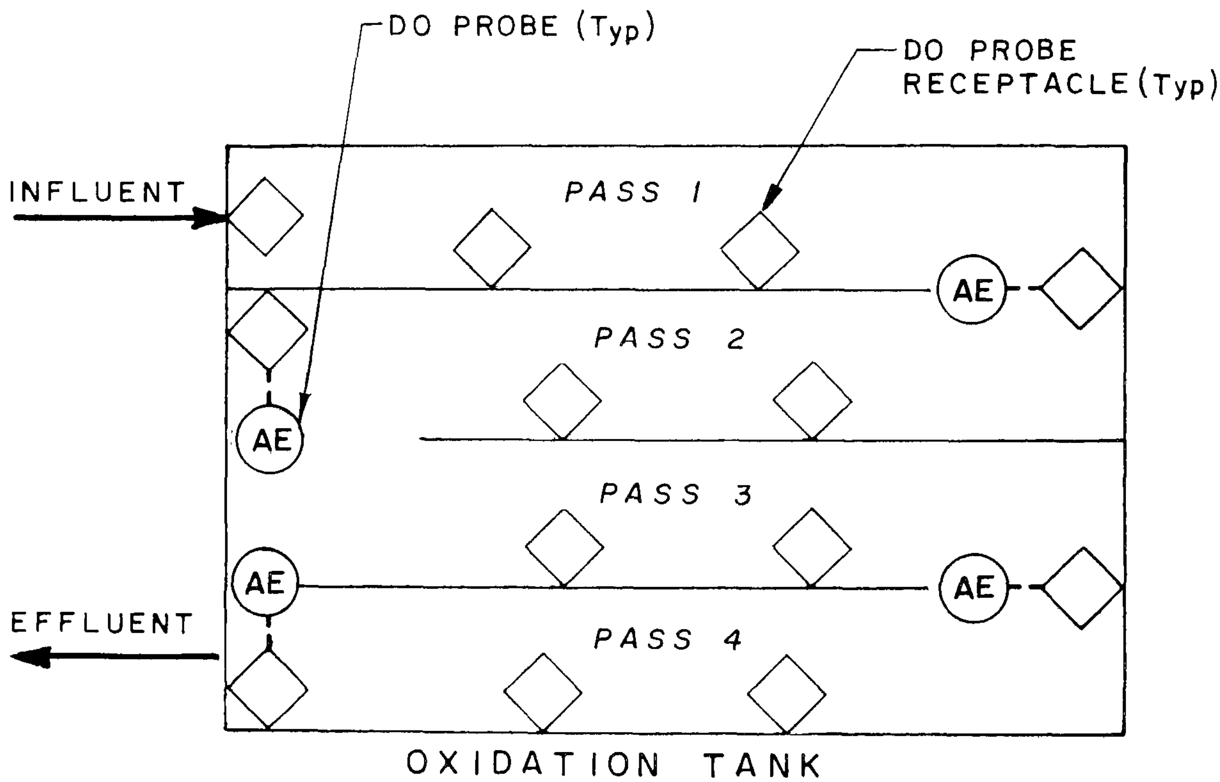


Figure 45. Plug flow, multiple pass oxidation tank - probe/receptable locations

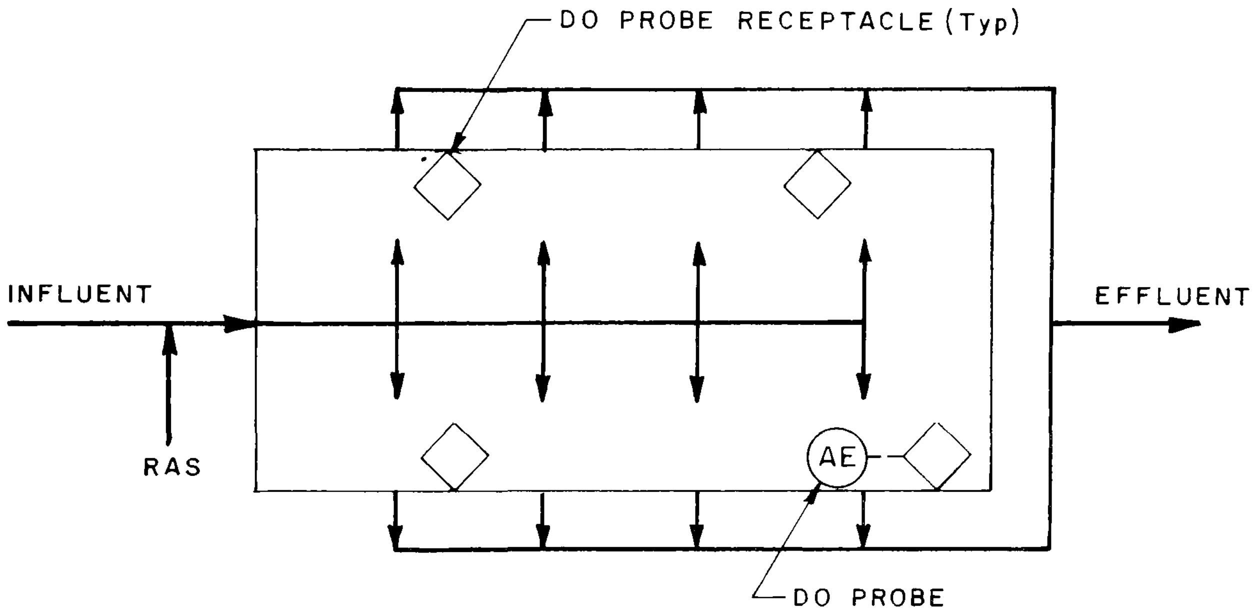


Figure 46. Complete mixed process oxidation tank - probe/receptacle locations.

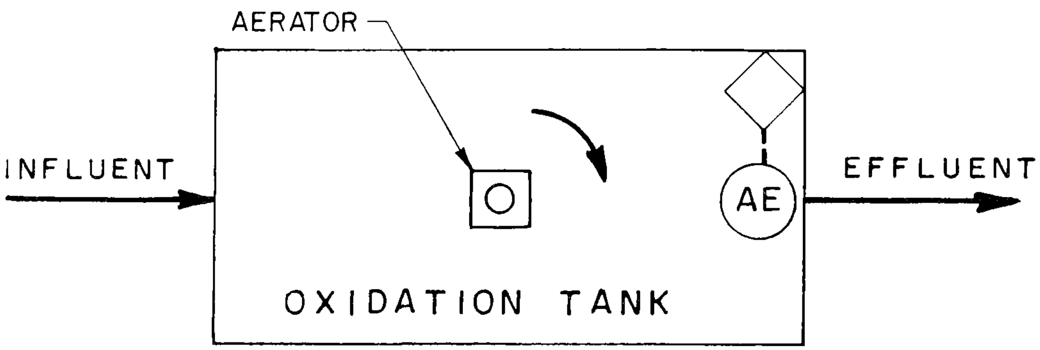


Figure 47. Single aerator installation - probe location.

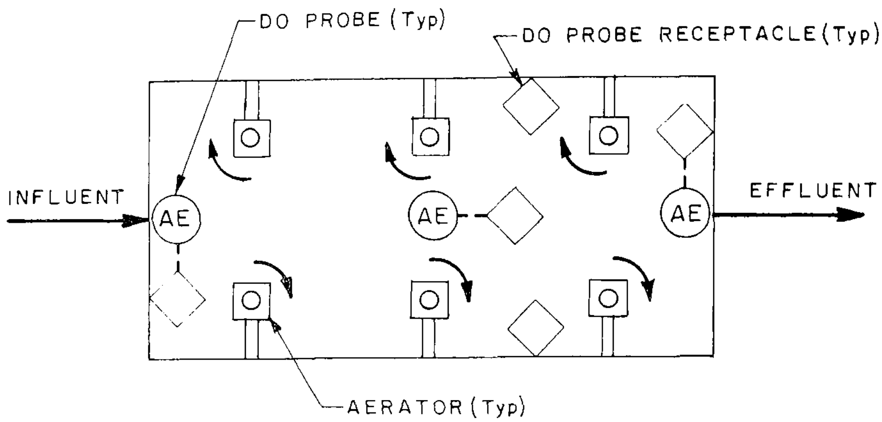


Figure 48. Multiple aerator installation - oxidation tank probe/receptacle locations.

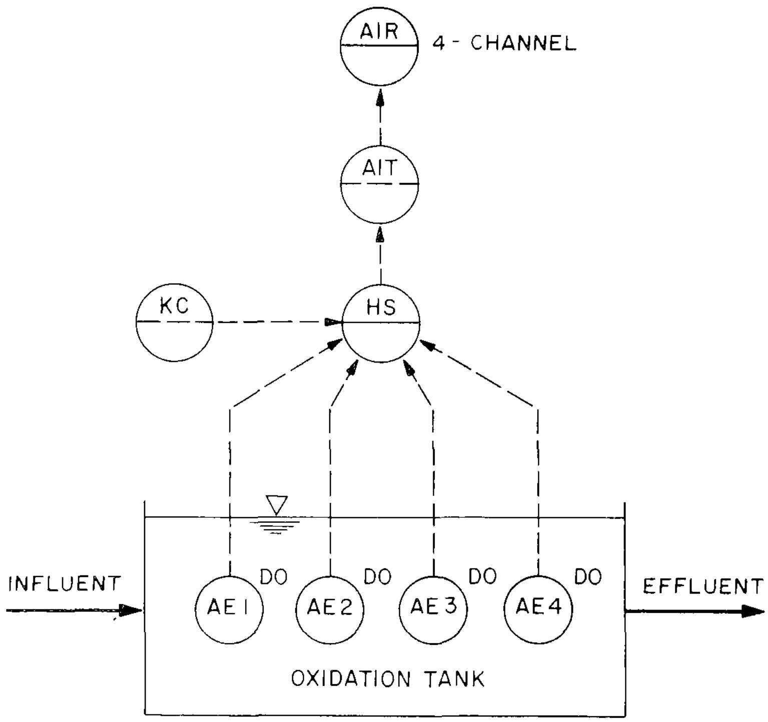


Figure 49. Multipoint dissolved oxygen monitoring system using a single, multiplexed analyzer.

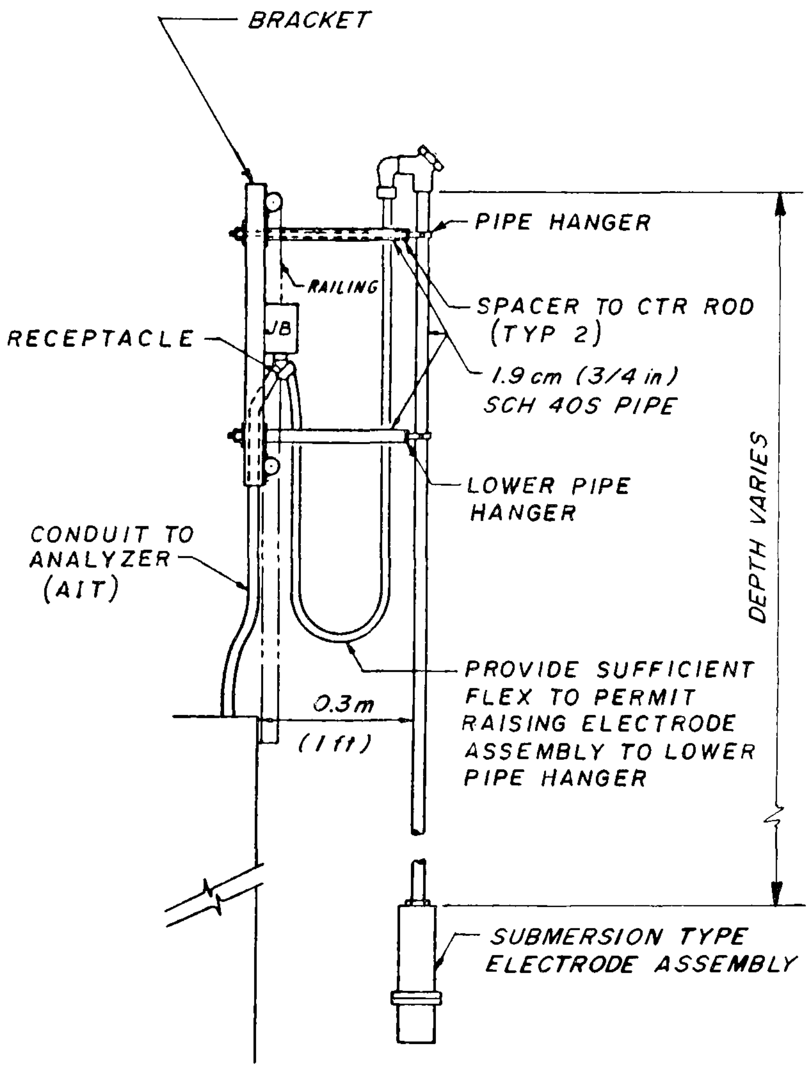


Figure 50. Dissolved oxygen probe assembly.

Calibration

The recommended procedure for calibration of a DO probe is to remove the probe from the mixed liquor, rinse it off to remove accumulations of solids and then place it in a bucket of tap water. The DO concentration in the water is previously determined by Winkler titration. For convenience, the sample of water should be slightly warmer than ambient temperature and nearly saturated with oxygen so that the DO level does not change significantly during the calibration procedure.

A second calibration procedure called "air calibration" is to remove the probe from the mixed liquor and permit it to stand exposed to the air for a period of from 5 to 15 minutes. The probe should be sheltered from the sun or rain. During the 5-15 minute period, the membrane will become dry and the probe assembly will approach ambient temperature. Under these conditions, the output from the probe is equivalent to saturated water at the ambient temperature since the partial pressure of oxygen in air is equivalent to the partial pressure of oxygen in saturated water. The ambient temperature can be read by switching the selector knob to the temperature position. Once the temperature is determined, the saturation value can be read from a table of DO values for pure water at saturation, and the calibrated output from the DO monitoring system can be adjusted accordingly. Alternately, calibration circuitry may be provided for direct calibration to percent oxygen concentration in air, avoiding the need for tables.

AIR AND PURE OXYGEN DISSOLUTION CONTROL SYSTEMS

A number of air and pure oxygen dissolution control systems can be employed for various modifications of the activated sludge process and various aeration methods. Three basic aeration systems are described, namely: diffused air aeration systems, mechanical aeration systems, and pure oxygen dissolution systems.

Diffused Air Aeration

Diffused air aeration is accomplished by introducing air under pressure as bubbles into the mixed liquor. Blowers of the positive displacement, centrifugal or axial type are used for air compression. Table 4 summarizes information concerning the application of various types of blowers used in diffused aeration systems.

In a multiple blower installation, a control system is required to start, stop and sequence the blowers to meet the air demands of the activated sludge process. A detailed description of the operation of a typical multiple blower installation is given below. Centrifugal blowers are described as they are most commonly employed for diffused air aeration.

Control of Centrifugal Blowers--

A typical schematic diagram for the control of multiple centrifugal blowers is shown in Figure 51 (Reference 9). The purpose of a blower control system is to match blower output to the total oxygen demand at all times. It should be noted that regulation of blower output does not directly control the amount of air put into the oxidation tanks or other air-demanding systems, such as channel aeration. Rather, the oxidation tank air demand is controlled solely by individual modulation of the oxidation tank air header valves in response to measured DO levels in the associated pass. Demand, therefore, is controlled solely by the needs of each system.

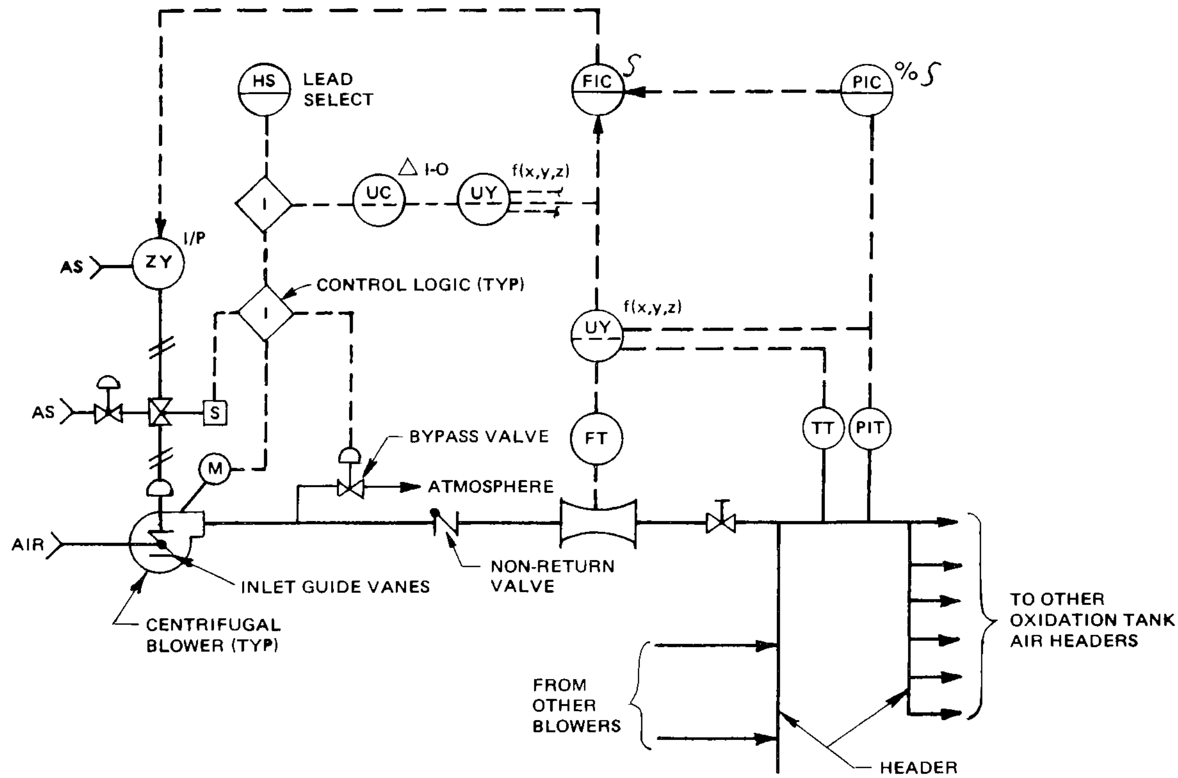


Figure 51. Diffused air aeration blower control system.

Blower volume control--The aeration air header pressure must remain constant at all times to ensure stable operation of the individual DO control loops. Typical means of ensuring that blower output matches demand is to regulate the speed, inlet guide vanes or suction throttling valves of all running blowers to maintain a constant preset pressure in the header.

As shown in Figure 51, each blower is provided with power-actuated inlet guide vanes and a low head loss flowmeter (FT) for the control and measurement of flow, respectively. The temperature and pressure of the air in the common air header is measured by a temperature transmitter (TT) and a pressure indicating transmitter (PIT), respectively. The signal from each FT is fed to a computing relay (UY) which also receives the temperature and pressure measurements from the TT and PIT. Computing relay UY solves the following equation and its output is volumetric flow at standard pressure and temperature, which serves as the controlled variable input to flow controller FIC.

The equation for converting actual m^3/s (acfm) to standard m^3/s (scfm) is as follows:

$$\text{standard } m^3/s = \text{actual } m^3/s \left(\frac{101 + P}{101}\right) \left(\frac{294}{T_K}\right) \tag{8a}$$

where P = pressure in kPa

T_K = temperature in degrees Kelvin

multiply m^3/s by 2120 for cfm.

In U. S. units the equation takes the following form:

$$\text{scfm} = \text{acfm} \left(\frac{14.7 + P}{14.7}\right) \left(\frac{530}{460 + T}\right) \tag{8b}$$

where P = pressure in psig

T = temperature in °F

One pressure controller (PIC) is provided which compares the actual header pressure to the desired pressure (set point). The output from the PIC serves as the set point for the FIC associated with each blower. The output from each FIC is fed to a current-to-pneumatic converter (ZY) which in turn produces a pneumatic signal that positions the inlet guide vane assembly on the associated blower.

The control system, which can be described as a pressure-to-flow cascade control system, is employed to ensure a specific discharge header pressure is constantly maintained and all operating blowers produce the same output. For example, if supply exceeds demand, the header pressure will start increasing; the output from controller PIC will then reduce and the inlet guide vanes will be further throttled until supply again matches the demand. The reverse is true when demand exceeds supply.

Blower starting/stopping control--In addition to modulating blower output to match demand, the control system is designed to start and stop blowers to match their capacities to the output required. Figure 52 shows a typical centrifugal blower starting/stopping sequence diagram. Under conditions of rising air demand, an additional blower is started when the power consumption (measured by wattmeters) or the mass flow (volumetric flow compensated for temperature and pressure) of the running units indicates they have reached maximum rated output. Under conditions of falling air demand, the last started blower is stopped when one less blower will give the output required. It is always more economical to run the least number of blowers that will meet demand.

The criterion used by the control system to test if remaining blowers can satisfy the air demand is: if the average blower discharge is less than $x(n-1)(n^{-1})$, then the last-started blower is stopped, where: n = number of operating blowers and x = maximum rated output of one blower. Duty rotation, i.e., rotating the assignment of blowers to lead and follow duty, is performed by the operator via lead selector switch HS shown in Figure 51. Rotation of blower duty should be practiced to equalize running times of all units.

Parallel operation of centrifugal blowers--If the centrifugal blowers are operated in parallel, each should be provided with its own surge control system, and the outputs of all operating blowers should be modulated uniformly. It is very difficult to operate one variable speed blower in parallel with a number of fixed "wide open" blowers which can be cut in or out as demand varies. To do so, the variable speed units must be of considerably larger capacity than the others, because of the relatively small flow turndown ratio. (In general, the surge line for variable speed operation limits the useful rangeability of a blower to about a 2:1 flow turndown; the rangeability of blowers with inlet throttling is usually at least a 3:1 flow turndown (5).) This would require different blower characteristics and, therefore, an expensive spare unit. It is preferable to modulate all operating blowers together and choose unit capacities small enough so two units are required at minimum flow. This control system can be applied to any activated sludge process flow scheme because the DO in each tank pass can be independently controlled.

Process Configurations--

Three basic process configurations applicable to diffused air aeration systems are described below.

Plug-flow, single pass--Oxidation tanks with a large length to width ratio are generally designed to pass the mixed liquor through the oxidation tank on a plug-flow basis. Biological stabilization proceeds more rapidly near the oxidation tank inlet, where substrate concentration is highest,

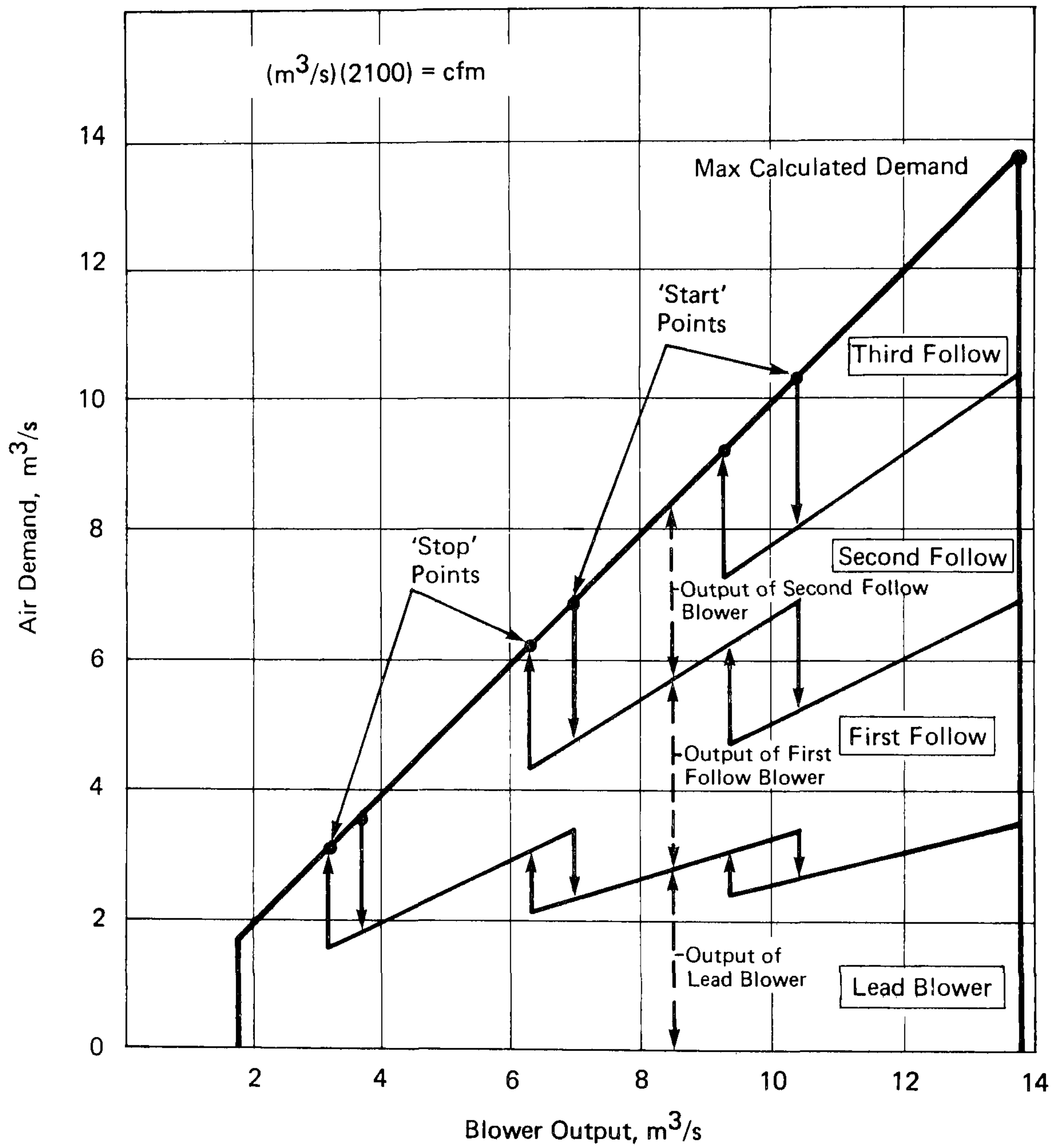


Figure 52. Typical centrifugal blower starting/stopping diagram.

thereby implying highest oxygen demand. Since it is desirable to maintain aerobic conditions at all points in the oxidation tank pass, it is recommended that DO probe receptacles be provided near the inlet, middle, and end of a plug-flow oxidation tank.

Plug-flow, multiple-pass--Multiple-pass oxidation tanks may be considered the equivalent of a folded, single-pass oxidation tank. Therefore, control logic applicable to multi-pass tanks is essentially the same as in the single-pass oxidation tank. DO probe receptacles should be provided near the inlet, middle and end of each pass.

Completely mixed--Completely mixed aeration provides for the equalization of the oxygen demand throughout the oxidation tank and a more uniform DO concentration. In systems where a completely mixed operating regime is approximated, probe location in the oxidation tank is less critical. However, long tanks may not accomplish complete mixing, thereby developing a gradation of oxygen demand from one end of the tank to the other. Flexibility in DO probe location is therefore recommended.

Typical Diffused Air Aeration Control Systems--

A typical diffused air aeration control system is shown in Figure 53. This control system can be applied to any of the activated sludge process flow configurations described in Section 4, because the DO in each tank pass can be independently controlled. The control system employs a cascaded configuration whereby the primary DO loop adjusts the set point of a secondary flow control loop. Although it is possible to use a single DO control loop to position the associated air control valve (particularly if the air header pressure is held constant), the cascade control loop approach is recommended to obtain good system stability and response.

The output signals from on-line DO probes require conditioning to minimize the effects of (a) DO probe noise, and (b) random noise caused by turbulent mixing conditions in the oxidation tank. Simple time-averaging and low-pass filters are considered suitable for estimating the true DO value from the real-time DO probe output signal.

The distribution of air from a tank pass air header is usually not automatically controlled. The DO control system goal is to meet the aggregate air demand of a given tank pass. Manual control valves are normally provided on each header downcomer feeding one or more air diffusers to permit balancing. If the operator wishes to change the air distribution along a given pass header, e.g., for tapered aeration, the manual control valves are used for this purpose.

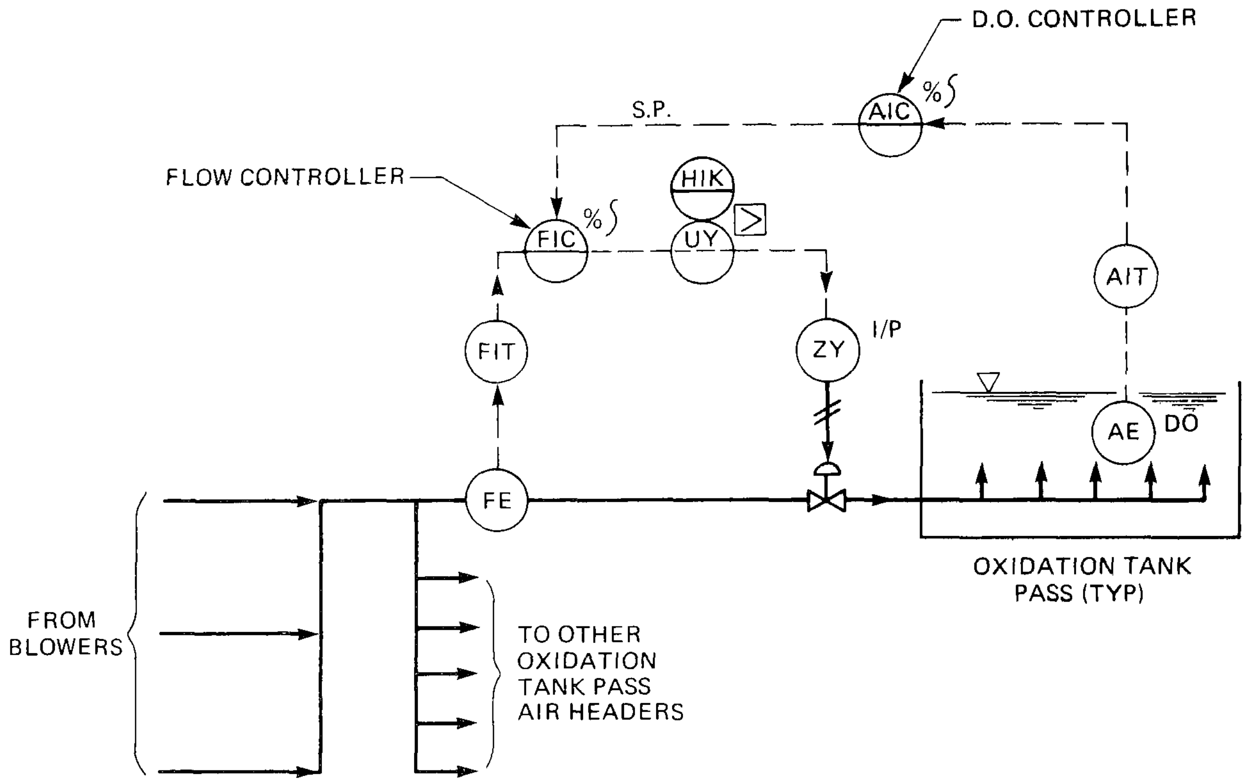


Figure 53. **Diffused air aeration dissolved oxygen control system**

Feedforward-Feedback Dissolved Oxygen Control Systems--

Two feedforward-feedback DO control systems that are currently being tested are shown in Figures 54 and 55. It should be noted that the limiting factor in matching the air/oxygen addition to an oxidation tank with a time-varying organic input load is the aeration equipment. If the aeration equipment does not have sufficient turndown, this deficiency cannot be remedied by the DO control system.

The total oxygen demand of the mixed liquor at the inlet end of the oxidation tank is time-varying. Furthermore, the oxygen demand at any point in the oxidation tank depends on the physical configuration of the oxidation tank with respect to influent and effluent structures, tank geometry and the type and location of the aeration equipment. As an example, in a typical plug-flow type activated sludge process, the oxygen demand is highest at the inlet end of the tank and gradually decreases to a minimum at the effluent end of the tank. In contrast, a completely mixed plant has a relatively uniform oxygen demand throughout the length of the tank.

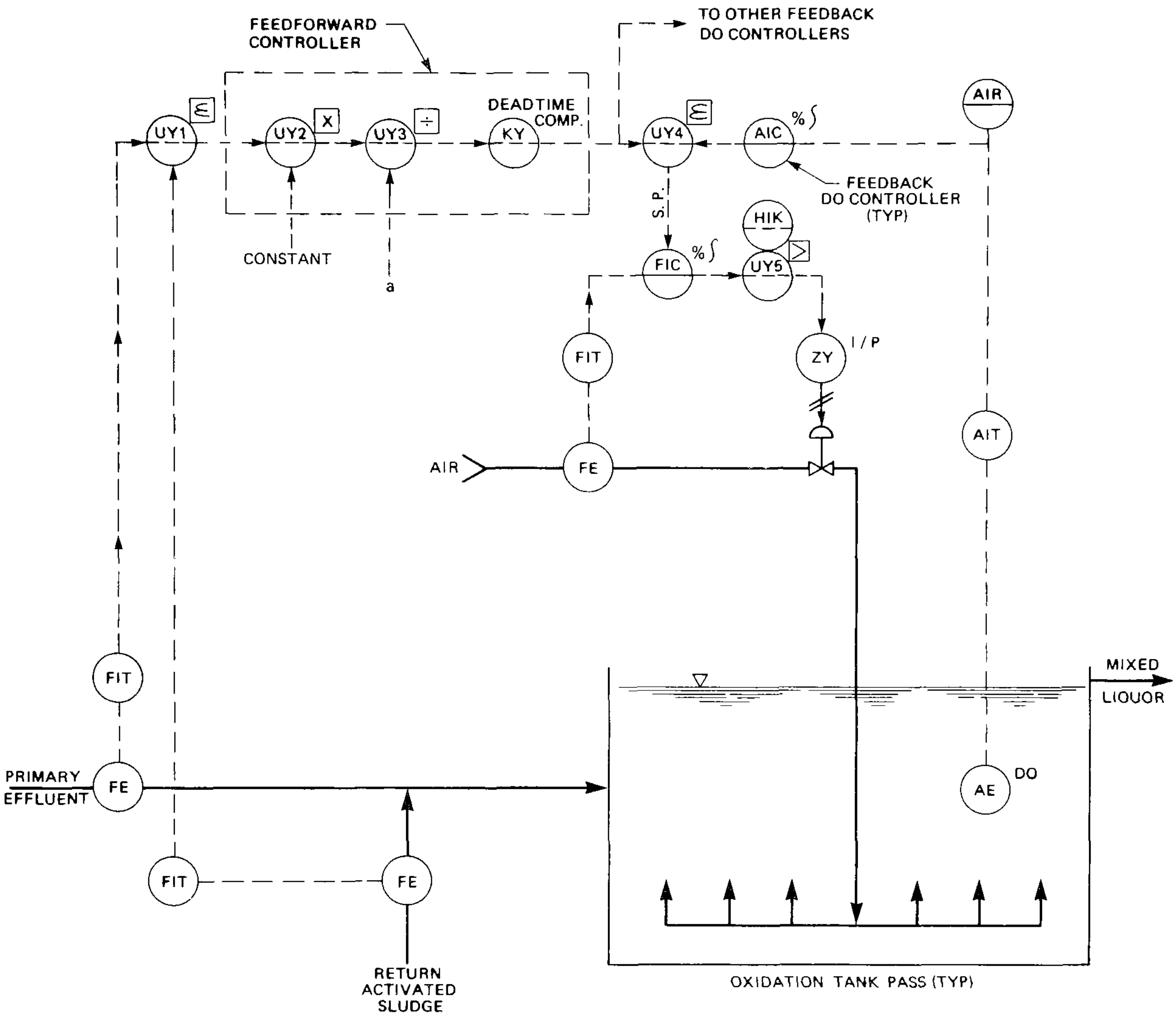


Figure 54. **Feedforward-feedback hydraulic load following dissolved oxygen control system**

Feedback DO control automatically compensates for all of the aforementioned load changes that can occur in the activated sludge process. However, because there is a time lag between a change in oxidation tank load and a corresponding change in the DO level in a given pass, feedforward control is recommended to reduce DO level variations in plants that treat wastewater with a highly variable oxygen demand.

With feedforward control, the basic concept is to measure the dominant load change and then feed it forward through a control strategy to all related manipulated variables. The feedforward model for each variable reflects the steady-state process relationships between the load change and the controlled variable. The feedforward DO control system continually balances the oxygen

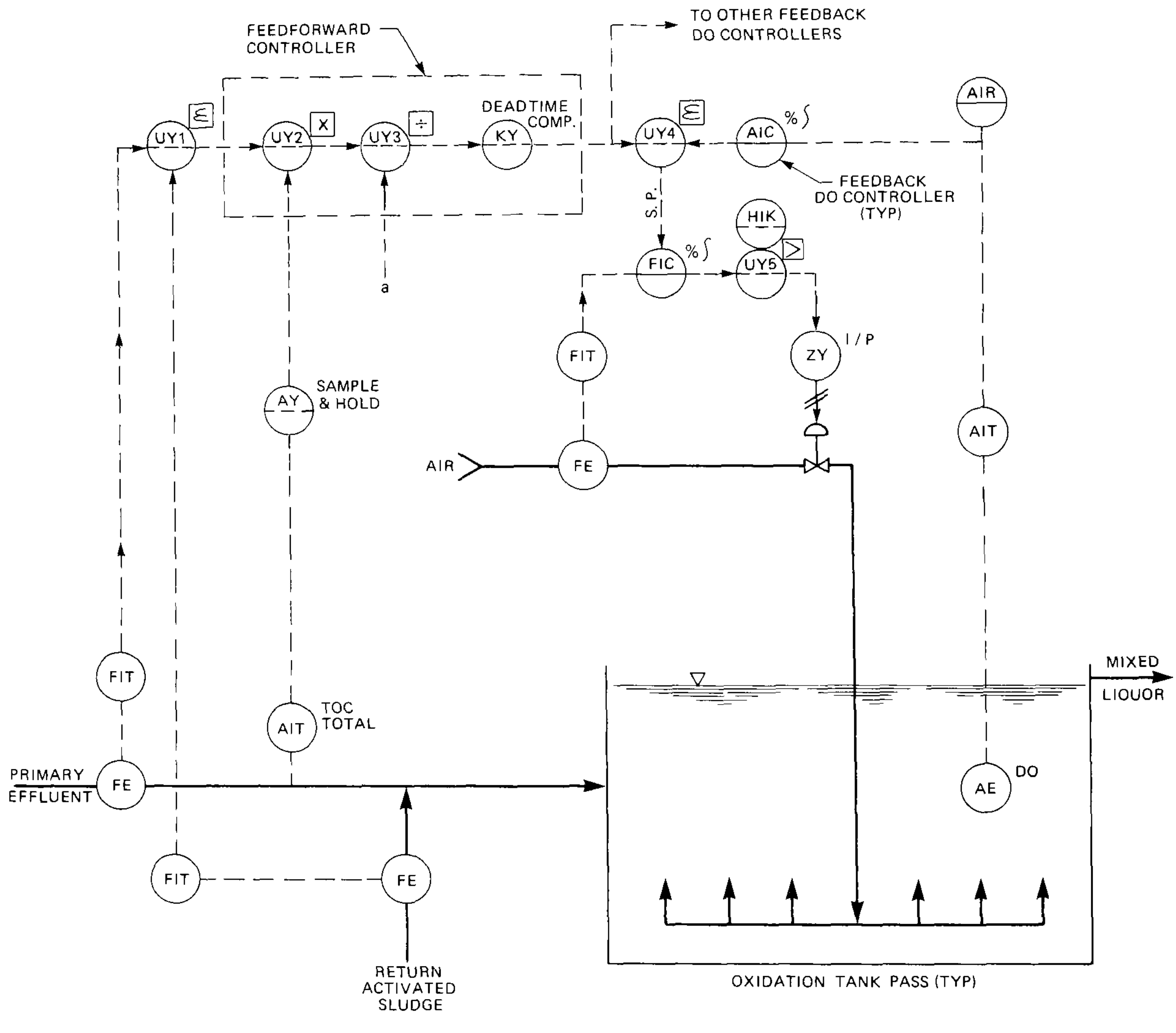


Figure 55. Feedforward-feedback hydraulic and organic load following dissolved oxygen control system

delivered to the oxidation tank against the estimated steady-state oxygen demand of the mixed liquor.

To correct for errors in the feedforward calculation, a DO feedback controller is linked to the feedforward control system. The difference between the set point and the output of the feedback controller is the offset that would have appeared if feedback had not been used. The outputs of both the feedforward and feedback control systems are summed, and the resultant signal is cascaded to the set points of the individual tank pass air flow controllers.

A feedforward-feedback DO control system incorporating hydraulic load following is shown in Figure 54. The basic feedforward strategy is to vary the air flow rate in proportion to the primary effluent flow rate and use DO feedback control to maintain the DO level at the desired value. The primary effluent flow rate is not usually measured directly; it is computed by summing the plant influent and recirculation flow rates and subtracting the primary sludge underflow rate. In the feedforward calculation, the primary effluent flow signal is multiplied by a constant (based on the average diurnal value of the mixed liquor oxygen demand). The output of UY1 is the estimated total air flow rate required.

The output from UY1 is divided by "a", a manual input that represents the number of oxidation tank air headers in service. The output of UY2 is the estimated air flow rate for a single air header. If the feedforward controller is implemented by digital logic, variable dead time compensation is provided via KY to account for the variable time delay between a load change at the oxidation tank inlet and an oxygen demand change in the tank. Unless the process is completely mixed, individual dead time compensation is required for each tank pass because the load change is reflected sequentially in each pass.

A DO probe is installed at an intermediate point in each pass. If the DO level in any pass deviates from a preset low value, the associated DO controller adjusts the output of the feedforward controller to correct the error. The resultant signal serves as the set point to the associated flow controller which, in turn, regulates the air flow to the particular pass. The flow controller is equipped with a minimum output limiter (HIK) to ensure adequate mixed liquor mixing at all times.

In Figure 55, a feedforward-feedback DO control system incorporating hydraulic and organic load following is presented. The oxygen demand of the mixed liquor at the influent end of the oxidation tank is estimated from an on-line, near real-time, total organic carbon (TOC) measurement and the sum of the primary effluent and return activated sludge flow rates. The feedforward air flow estimate using flow and TOC measurements is much more accurate than an estimate based on flow alone. However, the capital and operating costs of TOC analyzers are such that this technique may only be warranted for plants experiencing large variations in loading rate. On-line respirometers can also be employed to estimate the near real-time oxygen demand of the mixed liquor.

Mechanical Aeration

Mechanical aeration is accomplished by either transferring atmospheric or pure oxygen to the liquid by surface renewal and interchange or by dispensing compressed air or oxygen fed below the surface to a rotating agitator. As described in Section 5, mechanical aerators are broadly classified as plate, updraft, downdraft, combination and brush types. If the impeller diameter and tank area are fixed, the aeration capacity of mechanical aerators is a function of speed and immersion depth. Speed regulation, immersion depth control and intermittent operation modes are available for DO control.

Floating aerators inherently maintain a constant depth of submergence. However, platform or fixed-mounted aerators pose a problem in DO control because, unless the overflow or outlet capacity is quite large relative to the size of the oxidation tank, the water level and submersion will vary with flow fluctuations through the oxidation tank. Water level control is normally accomplished by the positioning of butterfly valves on the outlet piping or by sliding gates.

Process Configurations--

Two basic process configurations applicable to mechanical aeration systems are described below.

Plug flow--Oxidation tanks with large length to width ratios and containing several aerators, as shown in Figure 56, approach plug-flow conditions. The degree of mixing around the aerator at the influent end of the tank provides essentially complete mixing in its zone of influence, but the hydraulic translation from the zone of influence of the first aerator to the zone of influence of the second aerator progresses slowly, and the situation is repeated down the tank. As a result, the tank operates essentially like five smaller tanks in series, and the result approximates plug-flow rather than complete mixing conditions.

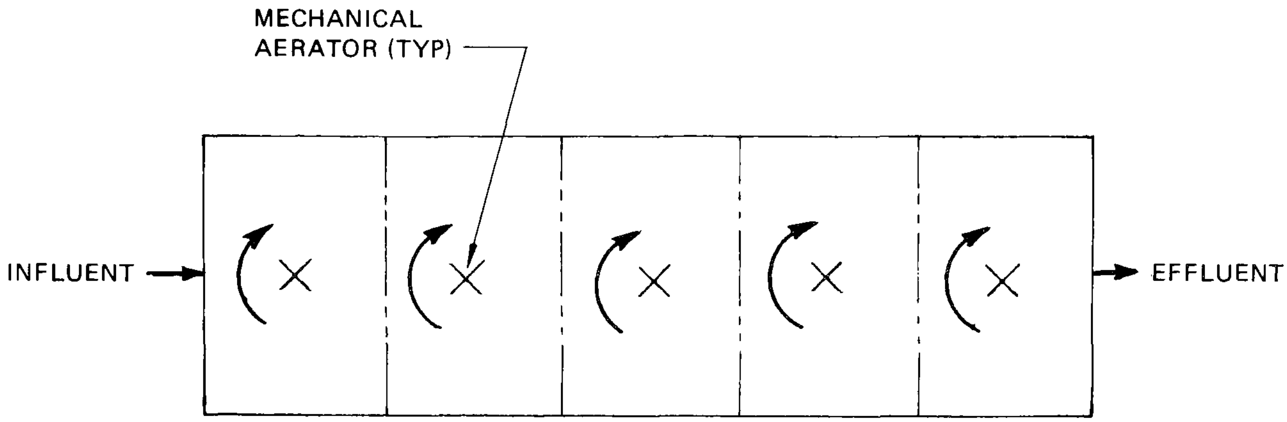


Figure 56. Mechanical aeration - plug flow configuration.

If adjustment of oxygen transfer capacity is applied to the entire tank (by procedures such as raising and lowering the effluent weir to change submergence of the aerators), the location of the DO probe should be left to the discretion of the operator, and DO probe receptacles should be provided so that the probe may be placed at either the influent end, the effluent end, or the middle of the tank.

If changes in aeration capacity are to be accomplished by speed changes of the individual aerators, the most advantageous control logic may not necessarily be speed changes on all aerators at the same time. For example, increased concentrations of wastewater influent will mainly affect the oxygen demand in the vicinity of the aerators at the influent end of the tank. Therefore, the influent-end aerators can be grouped for control of oxygen transfer capacity based on demand, and the remaining aerators can be controlled as a separate group. In general, adequate DO monitoring and control can be accomplished by placing the probes in the zone of influence of any aerator in a given control group.

Rectangular basin configuration--Where mechanical aerators are applied as shown in Figure 57, the problem of confined mixing around a given aerator exists in a similar manner to that suggested for the plug-flow configuration. For control purposes, aerators near the inlet or effluent ends of the tank may be grouped for collective control. In Figure 57, the five aerators at the influent end of the tank may be considered as a group, and speed changes for oxygenation capacity control can be made simultaneously to that group. Likewise, the five aerators near the effluent end may be controlled and considered as a separate group.

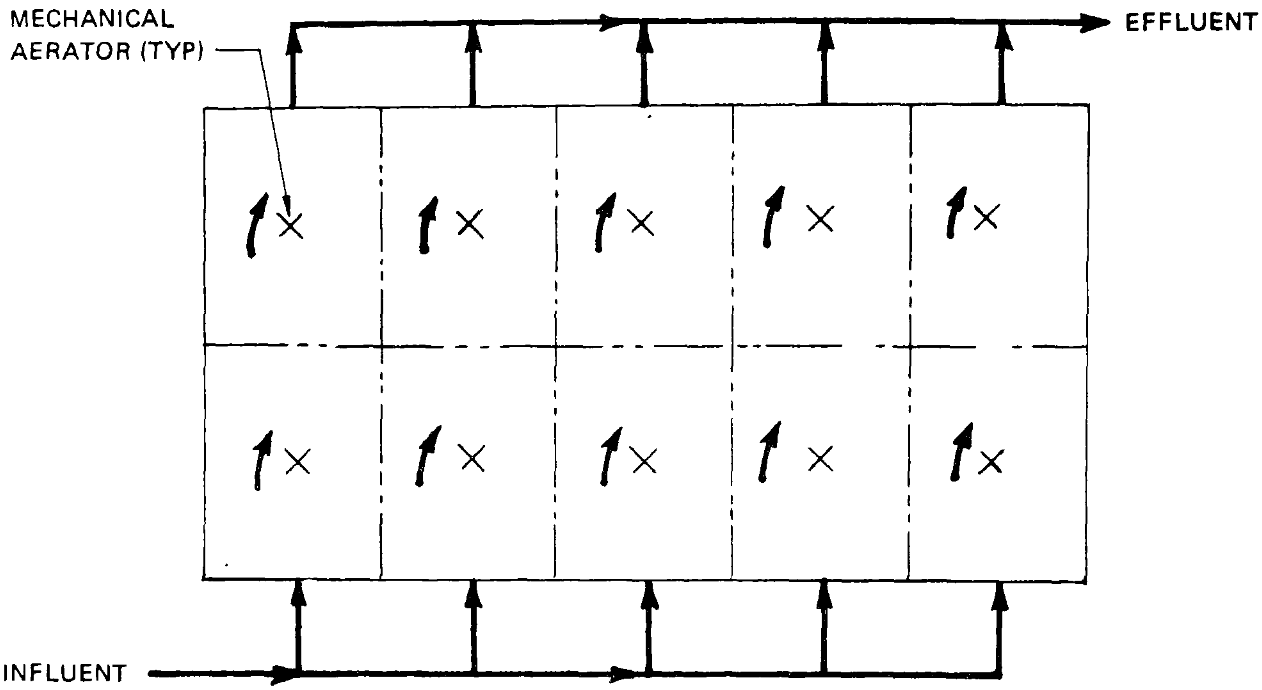


Figure 57. Mechanical aeration - completely mixed configuration.

Other aerator groupings might be considered so that smaller step changes in aeration capacity can be made. For example, the five aerators near the influent end of the tank may be subdivided into groups of two and three aerators. If this approach is taken, the isolation established by the zone of influence must be recognized. For example, if two-speed aerators are employed, and two aerators are on high speed while three aerators are on low speed, there is no single sampling point in the line of five aerators which represents the average impact of the transfer capacity. The impact can be averaged by integration of samples from the zone of influence of each aerator, but integration requires a complicated arrangement of pumped samples. A practical solution is to carefully select a probe location within the zone of one aerator so that acceptable information for control purposes is obtained.

In the application of mechanical aeration to rectangular oxidation tanks, the direction of rotation of the aerators should be considered. The objective is to select aerator rotations which do not establish a strong flow pattern along the line between aerators. For example, if the aerators in Figure 57 were arranged so that the aerators on the left rotated clockwise and the aerators on the right rotated counterclockwise, a strong short-circuiting flow would be established down the middle of the tank. Therefore, it is suggested that all aerators rotate in the same direction.

Mechanical Aeration Control Systems--

Five mechanical aeration control systems are described below and include the following: (a) on-off control, (b) two-speed control, (c) variable speed control, (d) variable impeller depth, and (e) variable level control.

On-off aerator control system--On-off aerator control is usually limited to oxidation tanks equipped with a single speed surface aerator(s). Furthermore, on-off operation should only be considered for wastes that do not exhibit pronounced separation characteristics. Settling tests should be made to determine whether on-off operation is feasible and, if so, the maximum "off" time that can be tolerated before liquid-solid separation occurs should be established. A typical on-off aerator control system is shown in Figure 58.

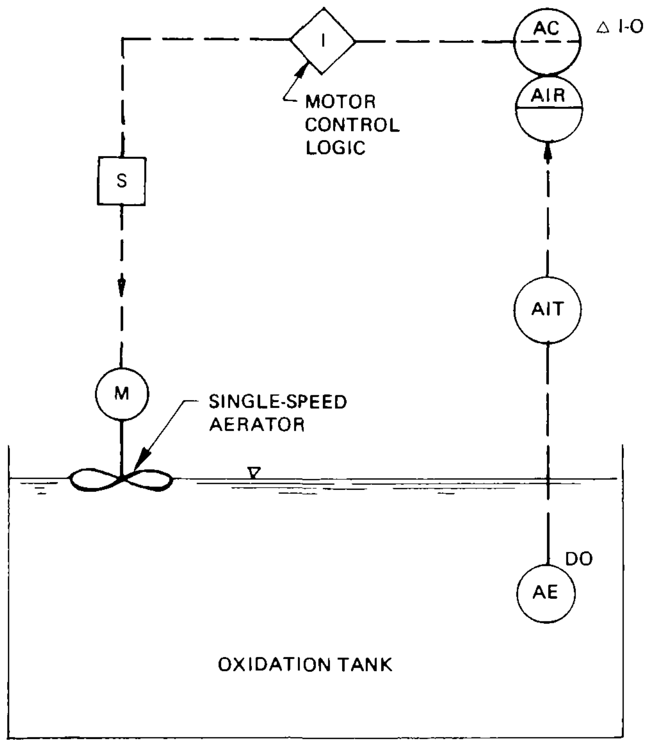


Figure 58. On-off aerator control system.

Two-speed aerator control system--A control system which is designed to maintain the DO level between preset high and low limits by adjusting the combined output of two-speed aerators is shown in Figure 59. Control systems of the step-control variety are often employed with final control elements that cannot be continuously output-modulated, such as two-speed

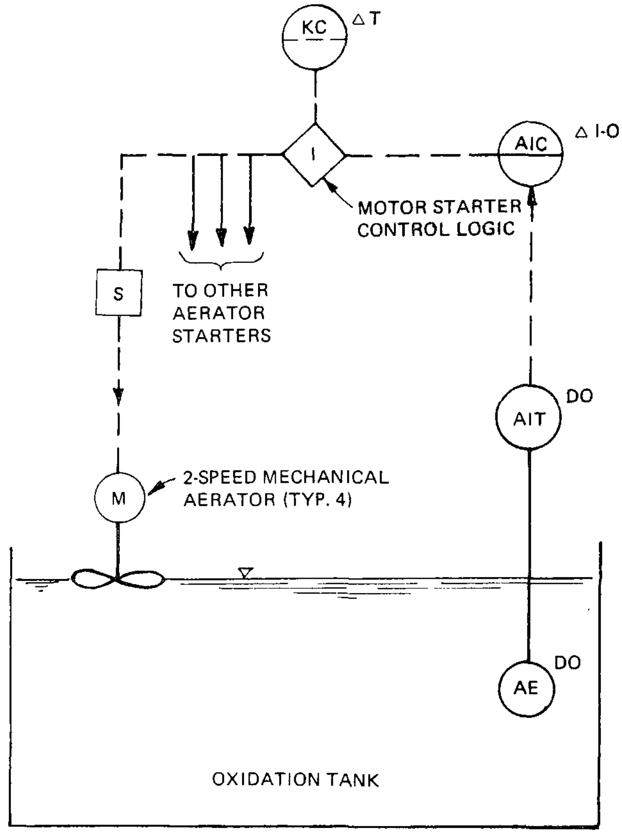


Figure 59. Two-speed aerator step control system.

mechanical aerators. Step control permits the time constant in the aeration system (reflected basically as the rate of change of oxygen demand in the aeration system) to be matched by step changes in aerator capacity taken at adjustable intervals of time.

The step change in aeration capacity can be accomplished by a predetermined change in mechanical aerator speed or any other operating step which will change the oxygen transfer capacity in the system. For example, Figure 60 shows a time step diagram for an oxidation tank with four two-speed aerators, where minimum capacity is defined as all four aerators at low speed and maximum capacity corresponds to all aerators at high speed. The time indicated as Δ T in Figure 60 is adjusted by the operator so the air supply approximately matches the instantaneous air demand of the aeration system. Timer KC in Figure 59 is adjusted so that at every preset time interval Δ T, the value of the DO signal input to control unit AIC is compared to preset high and low limits. If the DO level is at an intermediate value between the high and low limits, no adjustment to the aerator capacity is

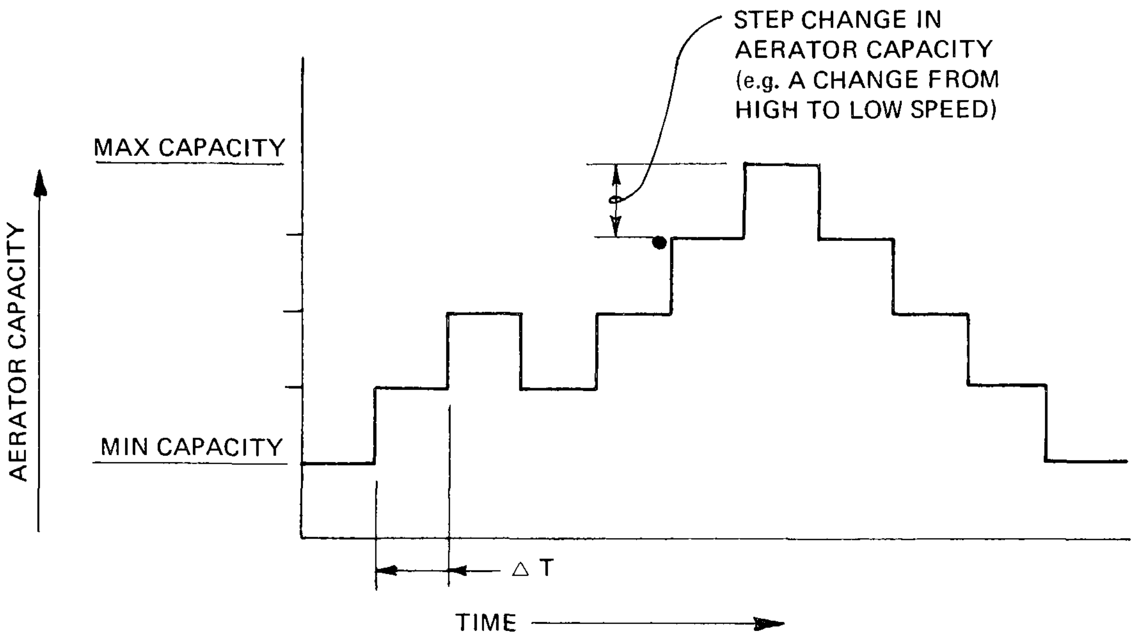


Figure 60. Aerator capacity/time step diagram.

made. If the DO level is lower than the preset low limit, the motor starter control logic steps upward by one capacity increment, and this new level of aerator capacity is sustained for the remainder of the time interval. At the end of the Δ T-interval, timer KC once more activates the control logic, and the DO level is again compared to the high-low limits which are preset in controller AIC. If the DO signal is lower than the low limit, another step upward in aerator capacity is made. However, if the DO signal is higher than the preset high limit, a downward step in aerator capacity is made. According to Woodruff (40), each step adjustment in oxygen transfer capacity should be at least 10 percent of the total oxygenation capacity of a given oxidation tank.

Variable speed aerator control--Large mechanical aerators are sometimes equipped with either variable speed motors or variable speed gear reducers. A typical variable speed aerator control system is shown in Figure 61. The speed of the aerator is modulated by controller AIC to maintain a preset DO level.

Variable impeller depth control system--The oxygenation capacity of a turbine aerator can be varied by adjusting the depth of submergence of the impeller blades. The impeller elevation is normally adjusted by means of an automatically controlled spline-type vertical shaft on the turbine aerator. The greater the blade submergence, the greater the oxygenation capacity of the aerator, and vice versa. A typical variable impeller depth control system is shown in Figure 62. A cascade control system is employed, whereby

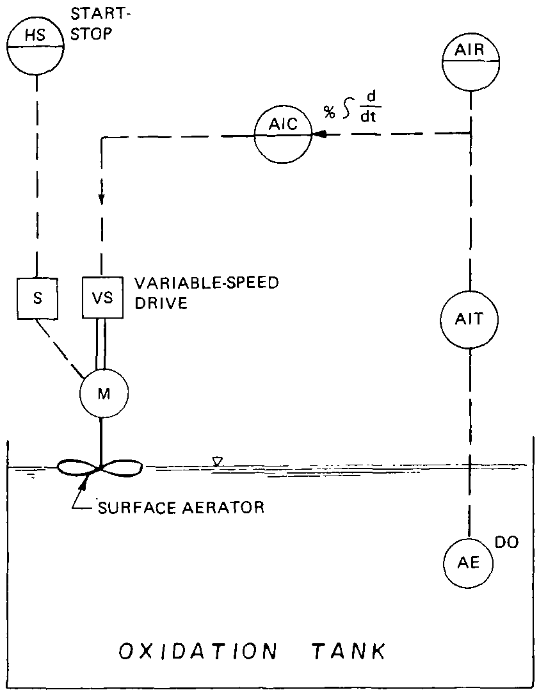


Figure 61. Variable speed aerator control system.

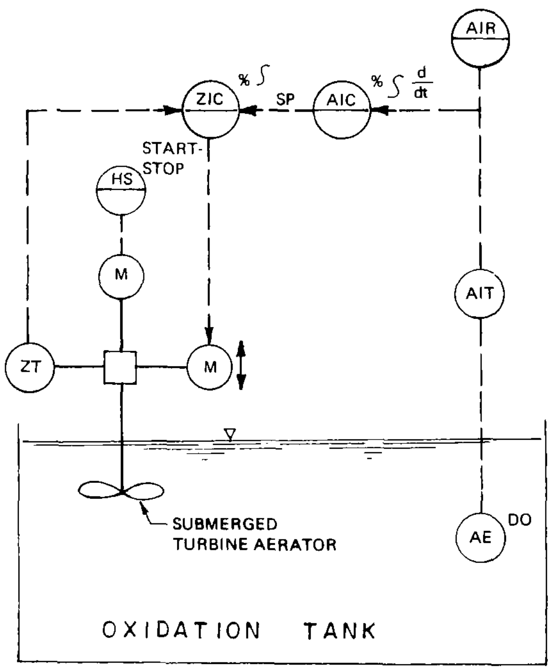


Figure 62. Variable impeller depth control system.

the output of DO controller AIC serves as the set point to submergence controller ZIC, which regulates the submergence of the turbine impeller to maintain the desired DO level in the oxidation tank.

Variable level control system--Another method of varying the oxygenation capacity of a turbine aerator is to control the liquid level in the oxidation tank and thereby control the depth of submergence of the turbine impeller blades. The liquid level can be controlled by raising or lowering a mechanical rotary weir. Weir positioning is accomplished by using a reduction gear and a motorized speed reducer. A typical variable level control system is shown in Figure 63. The output of DO controller AIC serves as the set point to weir position controller ZIC. The output from controller AIC adjusts the weir position, thereby regulating the liquid level and submergence of the turbine impeller to maintain the desired DO level in the oxidation tank.

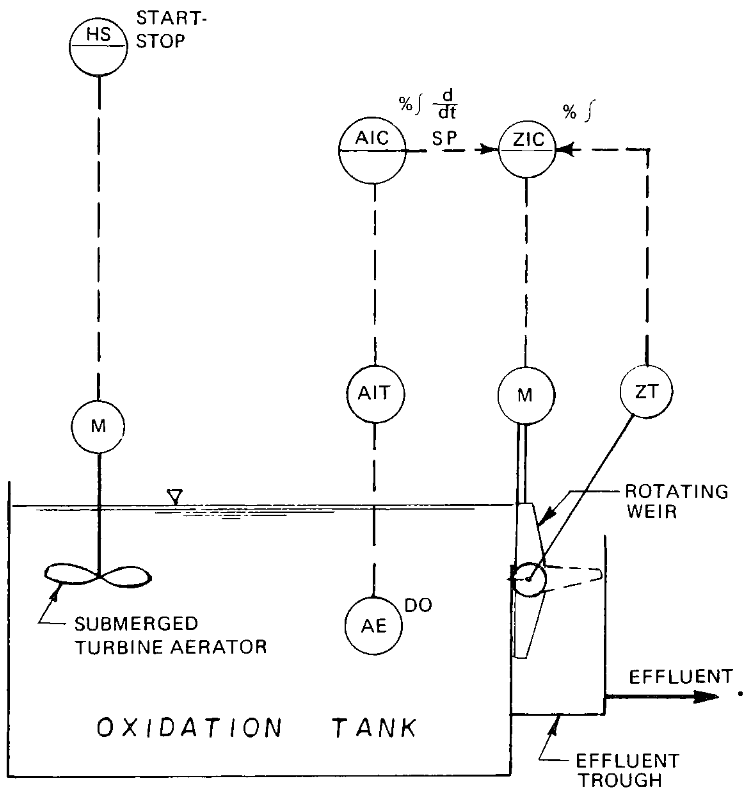


Figure 63. Variable level control system.

Pure Oxygen Dissolution Control Systems

When covered and staged oxidation tanks are used in the pure oxygen process to introduce oxygen gas into the mixed liquor, pressure control can be used to control the oxygen feed rate. A typical pure oxygen dissolution control system for a submerged turbine mixer and sparger system with recirculation compressors is shown in Figure 64 (Reference 9).

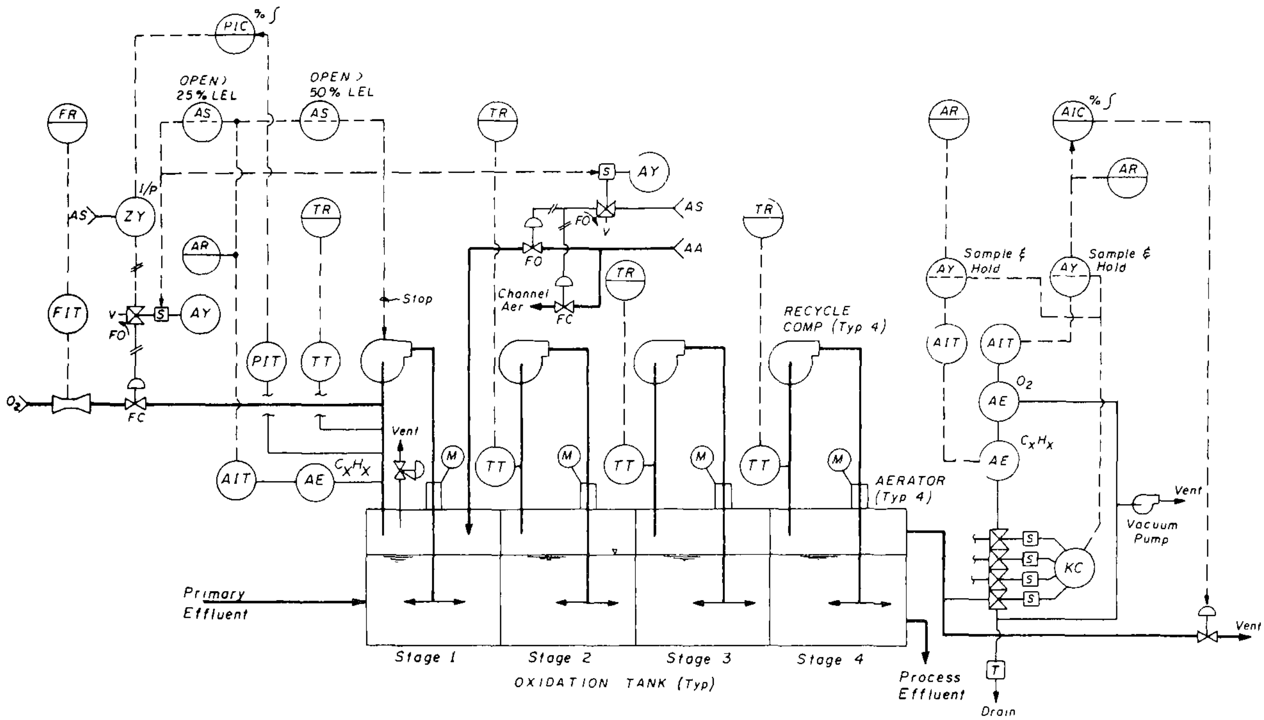


Figure 64. Pure oxygen dissolution control system.

Oxygen is introduced to each of the covered oxidation tanks in the first stage only and exhausted as vent gas from the final stage. The oxygen supplied to the first stage is controlled to maintain a constant gas pressure in the first stage of the oxidation tank by automatic modulation of a control valve on the oxygen supply header. The oxygen purity control system is designed to maintain constant oxygen purity in the gas venting from each oxidation tank by modulation of the vent gas valve. Pressure controller PIC and oxygen purity controller AIC maintain the pressure and oxygen purity set points, respectively, for each oxidation tank. The pressure and purity control systems interact as follows: A slight increase in oxygen demand in any oxidation tank causes a reduction in the oxygen purity of gas venting from the tank. Oxygen purity controller AIC compensates for this drop in purity by opening the vent gas valve, which causes a drop in pressure in the tank, thus causing a higher oxygen flow into the first stage of the tank. The system then stabilizes at a higher oxygen flow rate, while maintaining the same oxygen purity and gas pressure set points. An increase in oxygen purity at the vent valve causes a reduction in oxygen supply to the tanks. The system is designed to utilize 90 percent of the oxygen supplied.

SECTION 7

CASE HISTORY SUMMARY OF DISSOLVED OXYGEN CONTROL SYSTEMS

Performance, operational data, and maintenance data for aeration equipment and associated DO control systems in a number of activated sludge treatment plants, for both manual and automatic DO control, are presented in the Appendix. Performance comparisons made for each control mode include the following, where such data were available:

- BOD removal efficiency
- Suspended solids removal efficiency
- Sludge volume index
- Air supplied per unit quantity of influent
- Air supplied per unit quantity of BOD removed
- BOD removed per blower kwh

Considerable difficulty was encountered in obtaining useful DO control system data from most of the wastewater treatment plants that were contacted. Many of the plants are designed with automatic DO control systems, but these systems are not yet installed or are not being utilized. Other plants originally reported as having automatic DO control had only a remote manual control system. Typically, remote manual DO control in these plants involved reading DO levels on indicators in the control center and then manually initiating some control action, such as increasing mixer speed to raise the DO concentration to a desired value.

For the purposes of this study, the ideal plant control situation is one in which parallel oxidation tank units are operated simultaneously with one tank under manual and the other under automatic DO control. Such a situation occurred in the Rye Meads and Reno-Sparks studies.

The next best situation for a comparative DO control system study is a plant that is operated in a manual and an automatic DO control mode at different times over an extended period. This type of operation occurred at the Renton, Palo Alto and San Francisco International Airport plants.

The remaining plants reported in the Appendix currently operate in a manual or automatic DO control mode and required a special test for a comparative analysis. Short-term tests were devised to examine plant performance parameters under both modes of operation. It is recognized that data derived from such short experiments can be misleading, but it was felt that 48 hours of testing was all that could reasonably be requested of the plant operating personnel. In some cases, such as the San Jose-Santa Clara plant and the Reno/Sparks plant, the personnel expressed considerable interest in the study and elected to perform an extended test.

During both long- and short-term testing periods at some plants, problems arose, such as slug loads of jet fuel, storms, power failures, aeration equipment failures, misinterpretation of data desired or inadequate staffing for the specified sampling frequency on composite analyses. Data have been reported as received, with explanations furnished for inconsistencies.

TEST PROCEDURE

Where short-term DO control tests were performed for the purposes of this study, test data requested for each test were as follows:

1. Total air flow applied to the aeration tank (deduct air applied to other uses, such as mixed liquor channels).

2. Total influent to aeration tanks being examined.

3. Average BOD and suspended solids applied to the aeration tanks (24 hour composite analysis with samples taken every hour and stored at 3-4° C).

4. Average BOD and suspended solids in the plant effluent before chlorination (same type composite analysis as for No. 3 above).

5. Sludge Volume Index (SVI) on mixed liquor taken every four hours.

6. DO Concentration plot at the control probe.

7. Power consumption (kWh) of the blowers or mixers.

It was further requested that: days selected for the tests be typical of average conditions at the plant; DO should be maintained at approximately the same level in the oxidation tank during each test; manual control actions be performed approximately every four hours, unless the plant normally controls at some other time interval.

CASE HISTORIES

A total of 12 case histories are presented in the Appendix, covering a flow capacity range of 44 dm^3/s-4.38 m^3/s (1-100 mgd). Both municipal and industrial plants are included, with examples of constant and variable flow range facilities. All plants discussed use the activated sludge process with some also having tertiary treatment. The descriptive format for each case history is as follows:

Description of Aeration and DO Control System

Operation

Performance

Maintenance

Safety and Emergency Procedures

Table 5 lists the case histories studied with some brief descriptive data on each plant.

Table 6 summarizes plant loading, flow,and test duration data for each case history plant. Loadings and flows shown pertain only to that portion of the plant that was tested under manual and automatic DO control. Table 7 summarizes plant performance comparisons of manual and automatic DO control in terms of selected performance measuring parameters. As shown, data were not available from some plants for all parameters measured. Additional parameters measured and explanations for inconsistancies are in the Appendix.

Table 7 shows substantial improvements in the measured parameters occurring in a few plants and slight improvement in most others. Averaging the test data for each plant studied, excepting those noted, yields the results shown in Table 8. While results did differ between the case history plants studied, the conclusion is drawn from Tables 7 and 8 that automatic DO control generally results in improved plant performance and less dissolution energy consumption than manual DO control.

TABLE 5. CASE HISTORY PLANTS

Case number	Plant	Flow, m^3/s (mgd)	Type aeration	Flow scheme	Remarks
1	Renton Wastewater Treatment Plant, Washington	1.6 (36)	Diffused	Plug flow or step feed	
2	Palo Alto Water Quality Control Plant, California	1.5 (34)	Diffused	Plug flow or reaeration	
3	Rye Meads Sewage Purification Works, Hertfordshire, Eng.	0.69 (15.8)	Diffused	Plug flow	Fully nitrified effluents
4	City of Oxford Sewage Works, England	-	Diffused	Step feed	
5	Valley Community Services District Wastewater Treatment Plant, California	0.2 (4)	Diffused	Multi-mode	Fully nitrified effluent
6	Reno-Sparks Joint Water Pollution Control Plant, Nevada	0.88 (20)	Diffused	Multi-mode	
7	Simi Valley Water Quality Control Plant, California	0.31 (7)	Diffused	Plug flow, step feed, reaeration	Fully nitrified effluent
8	San Francisco International Airport Water Quality Control Plant, California	0.04 (1)	Mechanical	Plug flow, step feed	
9	St. Regis Wastewater Treatment Plant, Sartell, Minnesota	0.3 (7)	Mechanical	Plug flow	
10	Long Beach Water Renovation Plant, California	0.55 (12.5)	Diffused	Step feed	Fully nitrified effluent
11	San Jose-Santa Clara Water Pollution Control Plant, California	7.01 (160)	Diffused	Plug flow, step feed	Fully nitrified effluent, tapered aeration
12	Cranston Water Pollution Control Facility, Rhode Island	0.50 (11.5)	Diffused	Contact stabilization	

TABLE 6. SUMMARY OF PLANT LOADING, FLOW AND TEST DURATION DATA

Case number	Plant[a]	Test data					
		Test mode[b]	BOD loading, $mg/m^3/s$ (lb/1000 cf/day)		Flow, m^3/s (mgd)		Test duration
1	Renton	M A	3.95 5.86	(21.3) (31.6)	1.07 1.19	(24.5) (27.1)	3 months 3 months
2	Palo Alto	M A	4.52 5.23	(24.4) (28.2)	1.05 1.03	(24.0) (23.6)	1 month 1 month
3	Rye Meads	M A	4.71 4.56	(25.4) (24.6)	0.11 0.11	(2.5) (2.5)	6 months 6 months
4	Oxford	M A	no data no data		no data no data		Several months Several months
5	Valley	M A	6.80 5.19	(36.7) (28.0)	0.18 0.15	(4.0) (3.5)	48 hours 48 hours
6	Reno-Sparks, System 2	M A	4.86 3.97	(26.2) (21.4)	0.28 0.28	(6.3) (6.3)	48 hours 48 hours
	Reno-Sparks, System 3	M A	3.65 3.97	(19.6) (21.4)	0.28 0.28	(6.3) (6.3)	48 hours 48 hours
7	Simi Valley	M A	3.11 3.45	(16.8) (18.6)	0.20 0.21	(4.6) (4.7)	24 hours 24 hours
8	San Francisco A.P.	M A	3.89 7.49	(21.0) (40.4)	0.04 0.04	(1.0) (0.9)	1 month 1 month
9	St. Regis	M A	6.45 4.89	(34.8) (26.4)	0.25 0.24	(5.6) (5.5)	4 days 4 days
10	Long Beach	M A	3.86 3.32	(20.8) (17.9)	0.30 0.30	(6.9) (6.9)	24 hours 24 hours
11	San Jose Santa Clara	M A	10.1 10.4	(54.3) (56.1)	1.97 2.01	(45.0) (45.9)	4 days 4 days
12	Cranston	M A A	9.08 12.2 13.2	(49.0) (65.6) (71.3)	0.16 0.20 0.19	(3.6) (4.6) (4.2)	24 hours 24 hours 24 hours

[a] See Table 5 or Appendix for complete plant name

[b] M = manual; A = automatic

TABLE 7. SUMMARY OF PERFORMANCE COMPARISONS BETWEEN MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL

Case number	Plant[a]	Control mode and percent improvement[b]	BOD removal efficiency, percent	Suspended solids removal efficiency, percent	Sludge volume index (SVI)	Air supplied per unit volume of influent, m^3/m^3[c]	Air supplied per unit quantity of BOD removed, m^3/kg[d]	BOD removed per blower kWh, kg/kWh[e]
1	Renton	Manual	85		332	9.3	137	0.40
		Automatic	96		86	8.2	86	0.63
		% improvement	11		74	12	37	58
2	Palo Alto	Manual	84	46		3.3	33	1.3
		Automatic	84	53		3.4	28	1.6
		% improvement	none	7		none	15	23
3	Rye Meads	Manual	97	91	45	14	88	
		Automatic	98	92	79	11	71	
		% improvement	1	1	-76	21	19	
4	Oxford	Manual						
		Automatic						
		% improvement						
5	Valley	Manual	94	90	112	24	122	0.38
		Automatic	95	87	95	28	162	0.27
		% improvement	1	-3	15	-17	-33	-29
6	Reno-Sparks-2	Manual	92	83	113	10.5	110	0.55
		Automatic	78	86	108	9.5	140	0.29
		% improvement	-14	3	4	10	-27	-47
	Reno-Sparks-3	Manual	74	84	115	7.1	120	0.35
		Automatic	85	82	100	5.8	72	0.57
		% improvement	11	-2	13	18	40	63
7	Simi Valley	Manual	82	99	130	19.8	240	0.24
		Automatic	81	97	127	19.3	220	0.27
		% improvement	-1	-2	2	3	8	13
8	San Francisco A.P.	Manual	92	79	92			
		Automatic	94	96	201			
		% improvement	2	17	-118			
9	St. Regis	Manual	97	88	252			
		Automatic	98	89	201			
		% improvement	1	1	20			
10	Long Beach	Manual	97	90	99	27	190	
		Automatic	97	90	94	25	180	
		% improvement	None	None	5	7	5	
11	San Jose/ Santa Clara	Manual	85	86	102	6.7	600	
		Automatic	85	86	101	6.0	520	
		% improvement	None	None	1	10	11	-
12	Cranston	Manual	91	89	56	19	79	
		Automatic 1	94	96	60	15	58	
		% improvement	3	7	-7	21	27	
		Automatic 2	92	83	69	16	56	
		% improvement	1	-6	-23	16	29	

[a] See Table 5 or Appendix for complete plant name

[b] Percent improvement computed as automatic control over manual control. For BOD and suspended solids, percent improvement computed by subtraction. For remaining parameters, percent improvement computed by subtraction of values and division by manual value.

[c] m^3/m^3 multiplied by 0.134 = cf/gal

[d] m^3/kg multiplied by 16.02 cf/lb

[e] kg/kWh multiplied by 2.20 = lb/kWh

TABLE 8. TEST DATA AVERAGES OF CASE HISTORY PLANTS FOR AUTOMATIC COMPARED TO MANUAL DISSOLVED OXYGEN CONTROL

Parameter	Number of tests	Average percent improvement
BOD removal efficiency[a]	12	2.8
Suspended solids removal efficiency[a]	10	2.3
Sludge volume index[b]	11	2.6
Air supplied per unit volume of influent[c]	10	12
Air supplied per unit quantity of BOD removed[a]	9	21
BOD removed per blower kWh[a]	5	33

[a] Excepting Valley and Reno-Sparks System 2

[b] Excepting San Francisco Airport

[c] Excepting Valley

DISSOLVED OXYGEN CONTROL SYSTEM DESIGN ERRORS AND PROBLEMS

While gathering information on activated sludge plants for this manual, many design errors and problems were discovered in the application of dissolved oxygen control systems. In some cases, where problems were relatively simple, such as replacement of corroded aluminum DO probe terminal connections with noncorroding ones, or adding sealer to DO probe assemblies to prevent water intrusion, the plant has taken the necessary corrective steps. However, in many cases, where the designer had neglected to include a critical controller or had designed a DO control system where other critical processes were detrimentally affected by blower throttling, the plant has reverted to manual DO control.

Many plants investigated are designed with automatic DO control systems, but these systems are not yet installed or are not being utilized. A typical reason given for this situation is that the effluent meets required standards and the plant staff is occupied with more pressing matters. Failure of a critical component of the automatic DO control system, such as a DO probe or mixer variable speed relay, results in reversion to manual DO control. Since superintendents claim good quality effluent is produced under manual DO control, repairing the automatic DO control system becomes a low priority item.

Management at one plant waited almost two years after start-up to begin installing the DO probes necessary for the automatic DO control system. Unfortunately, many of the probes could not be made functional after that length of time and new probes had to be ordered.

One industrial plant reported that the DO control system for regulating surface aerator speed is so complicated that only the supplier can repair it. Consequently, after a few outages, the system was abandoned and the plant now operates in a manual DO control mode.

One design error observed was oversizing the throttling valve for air feed to oxidation tanks to accommodate future plant expansion. At present air flow rates, the plant finds no throttling effect is evident until the valve is 90 percent closed, resulting in poor air application control.

One plant studied was designed for multiple modes of activated sludge operation, but has operated in only the two-pass mode since start-up. When the superintendent was asked why he did not check on the efficiency of the other modes, he replied that alternate DO probe receptacles do not exist to permit effective DO control in any mode other than two-pass, and no funds existed in his budget to install them. He also added he had no inclination to change modes since the plant easily meets all effluent requirements.

Another plant has an automatic DO control system designed to throttle an air feed header butterfly valve in response to a DO signal received from the oxidation tanks. However, the slightest alteration in DO results in wide excursions of the butterfly valve, even with a tuned PID flow controller in the control loop. It was recognized later by the engineer that a cascade control system with a DO controller computing the set point of the flow controller would have been a better design. This plant is currently operated in a manual mode and produces an outstanding effluent. Thus, plant personnel have made no effort to rectify the automatic control system problem.

An additional design error discovered is utilization of positive displacement blowers to furnish air to a number of use points, such as aerobic digesters, channel aeration diffusers, return activated sludge air lift pumps and oxidation tanks, without any turndown provision. Throttling the air feed header butterfly valve to the oxidation tanks through a DO control loop results in more or less air to the other use points. A resultant increase or decrease in the return sludge rate is beyond the operator's control. Consequently, the plant is run under manual DO control with one blower at maximum capacity continuously and a second blower added during canning season. With at least one blower on at full capacity, plugging of the channel aeration headers is avoided.

Another plant is furnished with positive displacement blowers that supply air to both a contact and a stabilization tank. Air headers to each tank are throttled by separate DO control loops. After start-up, the operators observed that throttling the air headers was not very effective, since the blowers had no turndown capability and excess air could not be released. Accordingly, the plant installed a pressure reducing valve on the blower discharge manifold that vents to the atmosphere. Operating history indicates two blowers are operated continuously with constant venting of some discharge air. Power savings through DO control is, thus, nonexistent in this plant.

A major design error observed is incorporation of sophisticated automatic DO control equipment in a plant with a flow equalization basin or constant loading. The converse error observed was minimal DO control equipment in a plant that exhibits a daily flow variation of 5 to 1 but has no flow equalization basin. The first plant easily maintains a relatively constant DO concentration in the oxidation tanks by manual DO control. The second plant has difficulty maintaining an adequate DO level with a single DO probe and a mixer control system without automatic impeller submergence, variable speed, or other such air application control method.

Additional investigation of operating plants showed that adequate consideration is not given to maintaining mixed liquor solids in suspension in DO control system design. Operators of many plants with mechanical aerators cited mixing considerations as a major reason for abandoning automatic DO control in favor of manual control. The problem lies in sizing the mixer.

The mixer should be sized to maintain solids in suspension under existing and future loadings at low speed, while reserving high speed operation for additional oxygen as required. Operators of mechanically mixed plants that reported satisfactory operation at start-up frequently later found they had to operate the mixers at high speed most of the time to maintain solids in suspension, regardless of DO level

In general, more consideration should be given to proper blower selection, interdependence of process air systems, flow and loading variability, control system capabilities, expertise of control system in-plant maintenance personnel, control system flexibility, and adaptability to current as well as future plant capacity. It was evident in our investigation that automatic DO control is not warranted in every plant. An industrial or municipal sewage plant in which all blowers must be operated at full capacity on a continuous basis has no need for automatic blower throttling. The use of dual installed controllers and multiple DO probes for critical DO readings may be suitable for large scale wastewater treatment plants but may not be in the budget of a 44-438 dm^3/s (1-10 mgd) facility. However, a plant with a successfully operating automatic DO control system should not be dependent on a single DO probe with no spares, as was the case in one facility visited.

SECTION 8

COST OF AUTOMATIC DISSOLVED OXYGEN CONTROL SYSTEMS

While studying DO control systems at the twelve wastewater treatment plants, summarized in Section 7, it was apparent to the authors that a considerable variation exists in plant design, performance, aeration and DO control system design and operational flexibility. Comparing capital and operating costs of DO control system components in plants that have manual DO control with the same size plants having automatic DO control is unjustifiable because of the above mentioned variations. One solution to this problem is to apply capital, operation and maintenance cost data reported on specific components and types of control systems for actual plants to hypothetical plants of various capacities with assumed characteristics. Comparisons can then be drawn between the cost of manual and automatic DO control on a common basis by adding the incremental cost of automatic DO control to a plant having manual DO control.

DESCRIPTION OF THE HYPOTHETICAL ACTIVATED SLUDGE PLANTS

Five hypothetical plant designs with automatic DO control systems have been synthesized. These plants cover a plant flow capacity range of from 44 dm^3/s to 4.4 m^3/s (1-100 mgd) and were designed in accordance with (a) standards and guidelines referenced in this report, (b) information developed in the earlier chapters, and (c) accepted engineering practice. The designs are based on the conventional activated sludge process with either single or multiple-pass oxidation tanks. Table 9 shows the assumed design characteristics of the hypothetical plants.

Loading

BOD loading figures for each size plant were developed assuming combined wastewater collection systems and medium strength wastewater. An average 5-day BOD load of 200 ppm was used (6,7,20). An average of 5.6 mg/m^3 of aerator volume/s (30 lb BOD/1000 cf/day) is assumed (20,27). Considering this loading and an average influent BOD of 200 ppm, approximately 1.58 dam^3 (55,700 cf) of oxidation tank volume is required per 44 dm^3/s (1 mgd) of plant flow.

TABLE 9. DESIGN DATA FOR TYPICAL ACTIVATED SLUDGE PLANT AERATION SYSTEMS

Plant size, dm^3/s	44	44	440	2200	4400
Aeration type	Mechanical	Diffused	Diffused	Diffused	Diffused
Aerator type	Surface mechanical aerator	Positive displacement lobe type blower	Positive displacement lobe type blower	Single-stage centrifugal blower	Single-stage centrifugal blower
BOD loading, $mg/m^3/s$ (lb/1000 cf/day)	3.58 (19.3)	5.6 (30)	5.6 (30)	5.6 (30)	5.6 (30)
Air supplied, m^3/m^3 (cf/gal)		1 (7.5)	1 (7.5)	1 (7.5)	1 (7.5)
Number of oxidation tanks	2[a]	1	2	8	16
Number of passes	1	2	3	4	2
Oxidation tank dimensions length x width x water depth, Metres (Feet)	18x18x3.7 (60x60x12)	26x13x4.6 (84x44x15)	61x28x4.6 (200x90x15)	61x37x4.6 (200x120x15)	120x18x4.6 (400x60x15)
Pass width, Metres (Feet)	18 (60)	6.7 (22)	9.1 (30)	9.1 (30)	9.1 (30)
Number of mixers	2			-	
Number of blowers		2[b]	3[c]	3[c]	3[c]
Blower capacity, each, std m^3/s (scfm)		0.33 (700)	1.65 (3500)	8.49 (18,000)	16.5 (35,000)
Mixer or blower[d] power, kW (hp)	30[e] (40)	22[f] (30)	93.2[g] (125)	447[h] (600)	895[h] (1200)

[a] Each tank designed to treat 2/3 of the load.

[b] Blowers sized to each deliver 100% of air required.

[c] Blowers sized to each deliver 50% of air required.

[d] At 52 kPa (7.5 psig) discharge pressure.

[e] Based on 746 kW/28m^3 (1.0 hp/1000 cf) of oxidation tank volume.

[f] Assumed isothermal efficiency of 60%.

[g] Assumed isothermal efficiency of 70%.

[h] Assumed adiabatic efficiency of 78%.

Note: 1 dm^3/s = 2.28 x 10^{-2} mgd.

Number of Tanks and Dimensions

Most oxidation tanks in the United States are 4.6 m (15 feet) deep and are spiral flow type (2,34). References 2 and 27 specify a liquid depth of 3-4.6 m (10-15 feet). Each oxidation tank generally has 1 to 4 relatively narrow channels or passes since multiple passes control longitudinal mixing and short circuiting (39). Width to depth ratios for spiral flow tanks generally run from 1:1 to 2.2:1 with 1:2 being the limit recommended by Reference 2. The oxidation tank numbers and dimensions for each plant shown in Table 9 were determined using these guidelines and practical experience. Given the tank depth, oxidation tank volume required and acceptable width to depth ratios, tank lengths were determined based on a reasonable number of passes and accepted design practice.

Mechanical and Diffused Air System Considerations

Although mechanical aerators are used in activated sludge plants of all sizes, they are usually installed in plants up to 44 dm^3/s (1 mgd) in size. Reference 34 quotes another reference as saying the dividing line between diffused air and mechanical aeration is 44 dm^3/s (1 mgd). Another reference quoted in Reference 34 defines the division as 70 dm^3/s (1.6 mgd). It is also reported mechanical mixers are seldom used for plants that serve populations in excess of 5000 (34). Assuming 6.57 cm^3/capita/s (150 gpcd) as the average water supply and a 75 percent return of supply water as sewage flow, this converts the population figure of 5000 into a plant size of 24 dm^3/s (0.56 mgd). For the purposes of this study, it is assumed that plants of 44 dm^3/s (1 mgd) capacity would be furnished with either mechanical or diffused air systems. Larger plants are assumed to have diffused air systems.

Oxidation Tank Mechanical Mixer Selection

Oxidation tanks with mechanical mixers are usually square with 18m x 18m (60 x 60 feet) being common dimensions. Following the Ten States Standard (27) guidelines of a 3-4.6 m (10-15 feet) water depth, the tanks are designed to be 3.7 m (12 feet) deep.

Standby capability for diffused air systems is provided by adding an additional compressor. Standby capability for a mechanical aeration system is achieved by oversizing each oxidation tank. Design experience indicates oversizing each of two tanks to take two-thirds of the average plant loading is a reasonable approach. Accordingly, the BOD loading for the 44 dm^3/s (1 mgd) mechanical mixed plant in Table 9 is shown as only 3.5 $kg/m^3/s$ (19 lb/1000 cf/day) instead of 5.6 $kg/m^3/s$ (30 lb/1000 cf/day) as for the diffused air plants. The mixer horsepower selection is based on providing 26 kW/m^3 (1.0 hp/1000 cf) of oxidation tank volume.

Diffused Aeration Air Requirements

Aeration air requirements for conventional activated sludge plants are given in terms of cubic metres of air per cubic metre (cubic feet per gallon) of influent (3.7-11 m^3/m^3) (0.5-1.5 cf/gal) (7), cubic metres of air per kilogram (cubic feet per pound) of BOD applied (93.6 m^3/kg), (1500 cf/lb) (27) or cubic metres of air per kilogram of BOD removed (cubic feet per pound of BOD removed) (31-44 m^3/kg) (500-700 cf/lb) (34). Assuming a plant has an influent BOD_5 of 200 ppm and 35 percent of the influent BOD is removed in the primaries, results in 130 ppm of BOD_5 being applied to the oxidation tanks. Assuming a 90 percent BOD_5 removal in the secondary treatment stage, results in 117 ppm of BOD_5 being removed. Applying the above air flow rate guides to these figures results in air requirements ranging from 0.19-0.52 m^3/s (400-1100 scfm) of air for a 44 dm^3/s) (1 mgd) plant.

A more rigorous analysis utilizing equation (11) (taken from Reference 6) for oxygen required results in 15.3 g/s/kg MLVSS (1320 lb/day/lb MLVSS) (6):

$$\text{lb } O_2/\text{day} = aL_R + b \text{ (lb MLVSS)} \tag{11}$$

where a = 0.45 = fraction of 5-day BOD removed that is used to provide growth energy (typically 0.35-0.55)

b = 1.4 ug O_2/s/g (0.120 lb/O_2/day/lb) = endogenous respiration rate

MLVSS = 2100 ppm (assumed)

L_R = g BOD_5 removed/sec = 5.12 g/s (976 lb/day) for a 44 dm^3/s (1 mgd) plant with 117 ppm BOD removed

oxidation tank volume = 1.6 dam^3 (0.42 million gallons) for 44 dm^3/s (1 mgd) plant

Assuming an oxygen transfer efficiency of 8.6 percent (6,7), and using an air density of 1.20 kg/m^3 (0.075 lb/cf) and an oxygen content of 23.2 percent by weight results in 0.295 m^3/s (625 scfm) being required for a 44 dm^3/s (1 mgd) activated sludge plant with an assumed loading of 200 ppm BOD_5. Considering this result, along with other data available, results in an assumed air flow rate for the 44 dm^3/s (1 mgd) plant of 0.33 m^3/s (700 scfm) or about 7.48 m^3/m^3 (1.0 cf/gal) of influent.

Blower Selection

The assumption that the aeration system diffusers are located one foot above the oxidation tank bottom results in a static head of 42 kPa (14 feet) for the blowers to develop. A distribution system and diffuser loss of 25 percent of the mixed liquor depth is assumed, or 10.5 kPa (3.50 feet).

Summing the static and dynamics heads results in a required discharge pressure of 52 kPa (7.5 psig).

Blower types, sizes and number of units for each plant are selected in accordance with (a) the guidelines of Table 1, (b) field observation of existing installations and (c) practical experience. A 100 percent capacity standby blower for the 44 dm^3/s (1 mgd) plant is selected because it is judged more economical and practical to provide two complete 100 percent capacity units for the small size blowers required, rather than three 50 percent capacity units, as for the other diffused air plants. Since the aeration system is considered a critical plant process in maintaining required plant effluent standards, it is assumed the system should be capable of operation with the largest unit out of service. Loss of a single blower in any of the plants will, therefore, not degrade process performance.

Theoretical power requirements for the rotary, positive displacement, lobe type blowers are computed assuming isothermal compression according to the following formula:

$$kW = P_1Q_1 \ln(Q_2/Q_1) \tag{12a}$$

where P_1 = suction pressure, kPa

Q_1 = actual inlet flow, m^3/s

Q_2 = actual outlet flow, m^3/s

In US units the equation takes the following form:

$$ghp = (144\ P_1Q_1/33{,}000) \ln(Q_2/Q_1) \tag{12b}$$

where ghp = gas horsepower

P_1 = suction pressure, psia

Q_1 = actual inlet flow, acfm

Q_2 = actual outlet flow, acfm

Isothermal efficiencies of 60 percent and 70 percent are utilized in calculating the actual or brake horsepower requirements of the blowers for the 44 dm^3/s (1 mgd) and 440 dm^3/s (10 mgd) plants respectively.

Theoretical blower horsepower requirements for the centrifugal blowers are computed assuming isentropic (reversible adiabatic) compression according to the following formula:

$$kW = PQ \left[k/(1-k)\right]\left[r^{(k-1)/k}-1\right] \tag{13a}$$

where P = suction pressure, kPa

Q = actual inlet flow, m^3/s

k = Cp/Cv = ratio of specific heats = 1.395 for air

r = pressure ratio of discharge in kPa divided by suction in kPa

In US units the equation takes the following form:

$$ghp = 144\ PQ/33000 \quad \left[k/(1-k)\right]\left[r^{(k-1)/k}-1\right] \qquad (13b)$$

where ghp = gas horsepower

P = suction pressure, psia

Q = actual inlet flow, acfm

k = Cp/Cv = ratio of specific heats = 1.395 for air

r = pressure ratio of discharge in psia divided by suction in psia

An adiabatic efficiency of 78 percent was assumed for the centrifugal blowers in calculating the brake horsepower required.

Dissolved Oxygen Control Equipment

Figures 65 through 69 schematically illustrate the oxidation tank configurations, diffused and mechanical aeration equipment and DO control systems for the five hypothetical plants. The DO control systems presented reflect current practice and have a history of successful operation.

As shown in Figures 65 through 69, the DO probes are positioned for a plug flow operating mode. Alternate DO probe receptacles are provided to permit flexibility in DO probe placement if the plant operating mode is changed to step feed, complete mix, or other as provided in the plant design. Field experience indicates that plant operating modes are changed only once or twice per year. It is therefore assumed that the operator would recalibrate and relocate probes at alternate receptacles as necessary when the operating mode is switched. Since DO probe receptacle groups are wired into a common transmitter, plugging a DO probe into any of the receptacles in a given receptacle group automatically connects the probe output to the transmitter. If a DO probe malfunctions, the operator can either switch to another DO control probe by patching in another transmitter with a connected DO probe to controller AIC, or the defective DO probe can be replaced.

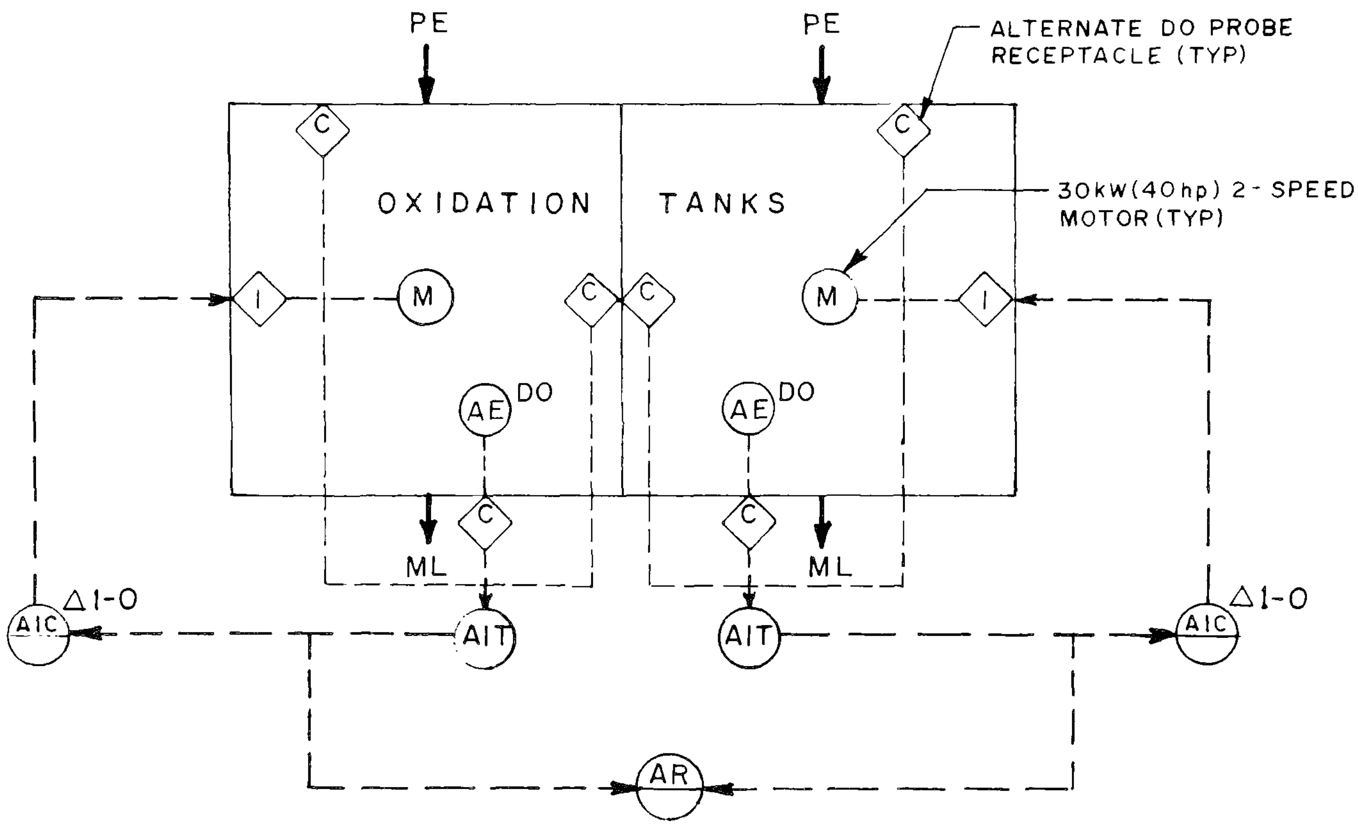


Figure 65. Automatic DO control system for mechanically aerated 44 dm^3/s (1 mgd) activated sludge plant.

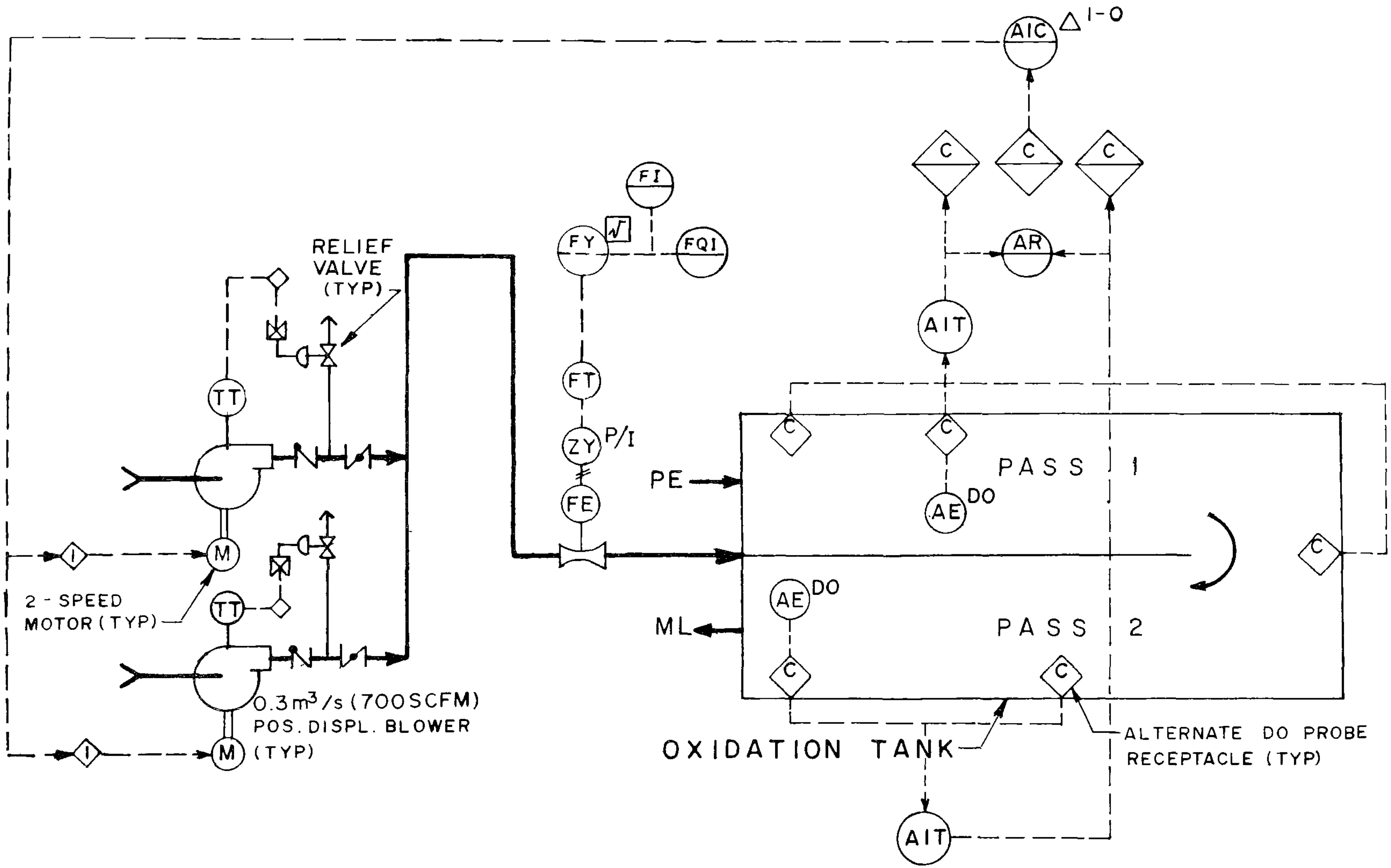


Figure 66. Automatic DO control system for diffused air 44 dm^3/s (1 mgd) activated sludge plant.

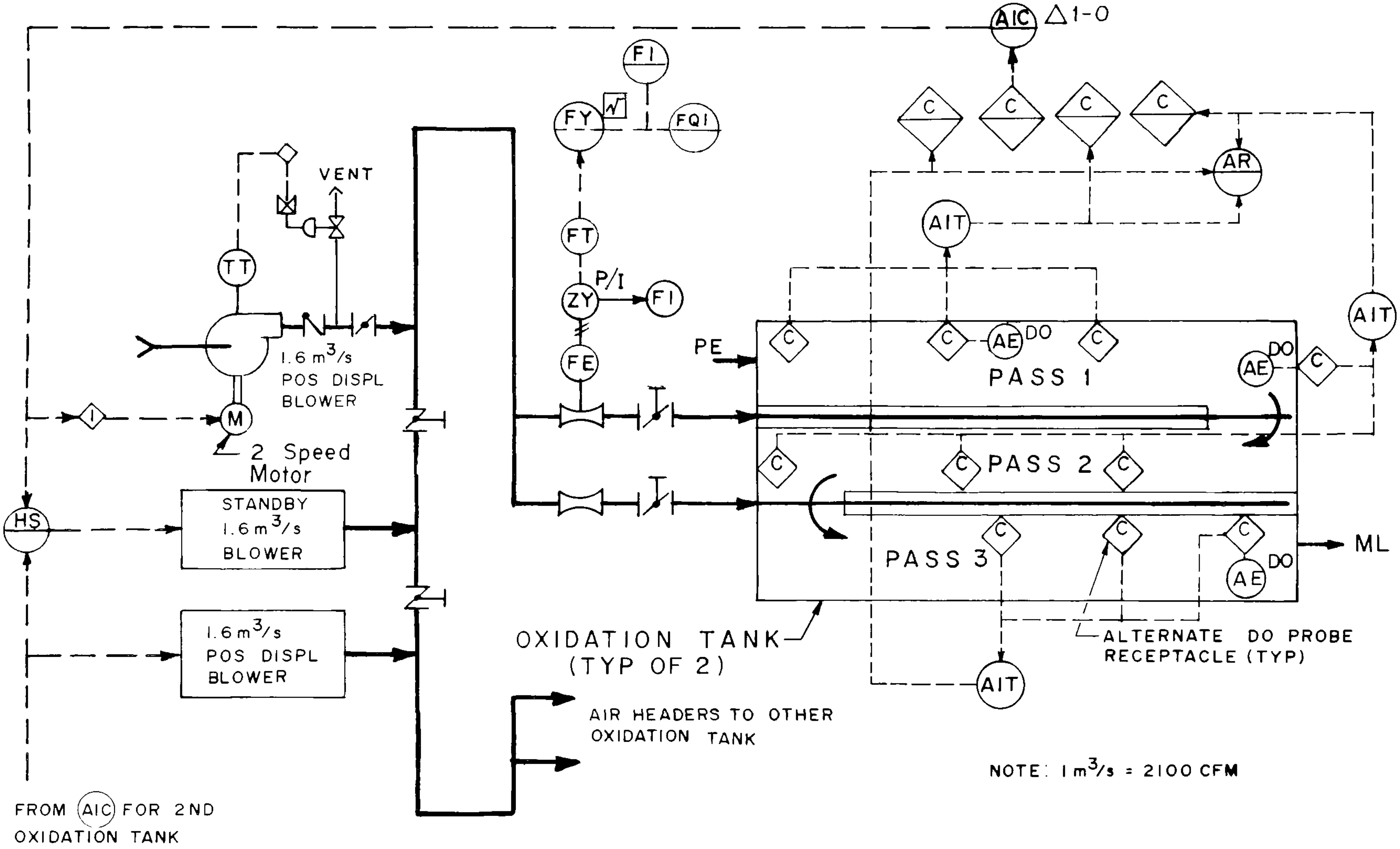


Figure 67. Automatic DO control system for diffused air 0.44 m^3/s (10 mgd) activated sludge plant.

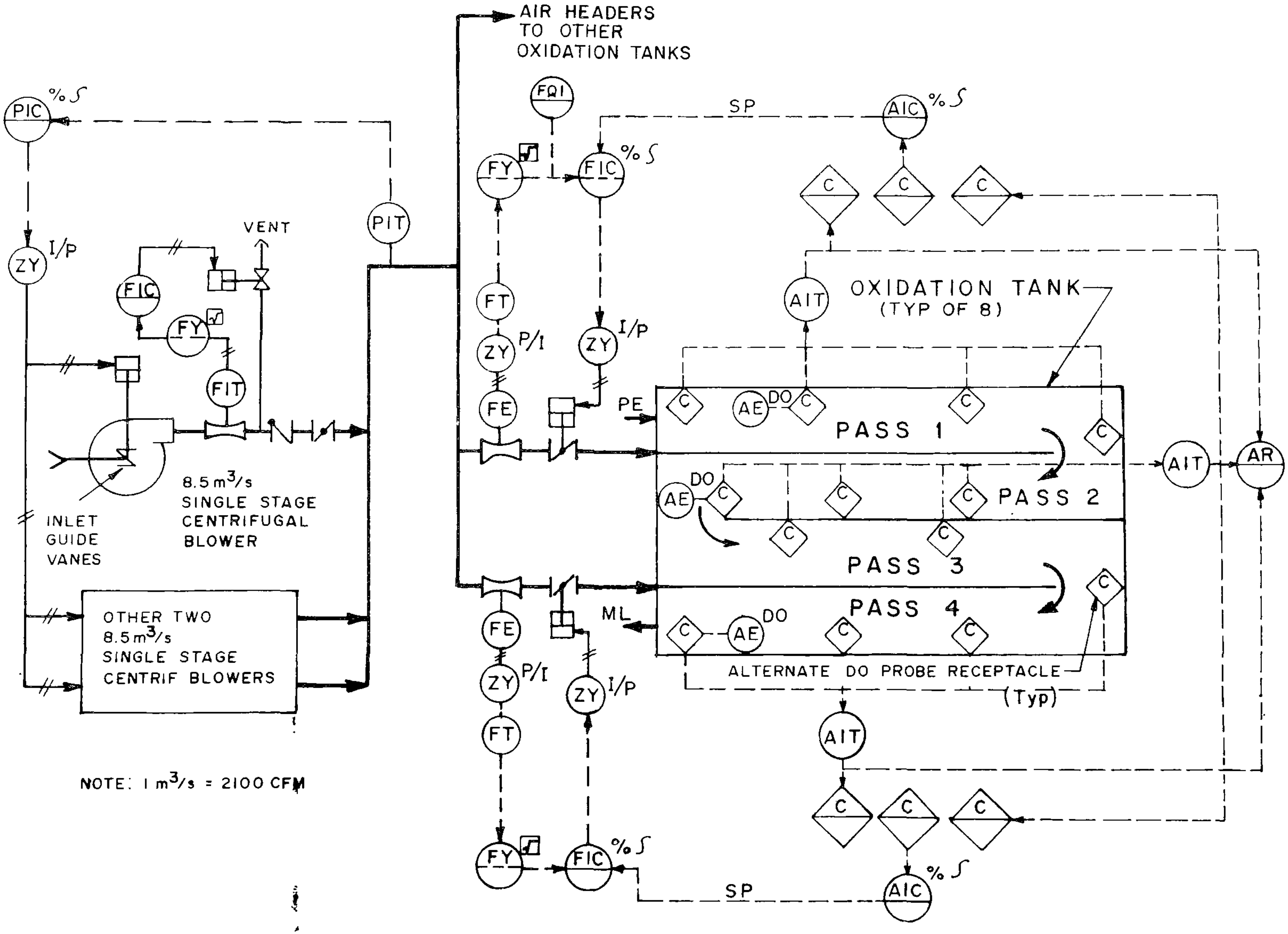


Figure 68. Automatic DO control system for diffused air 2.2 m^3/s (50 mgd) activated sludge plant.

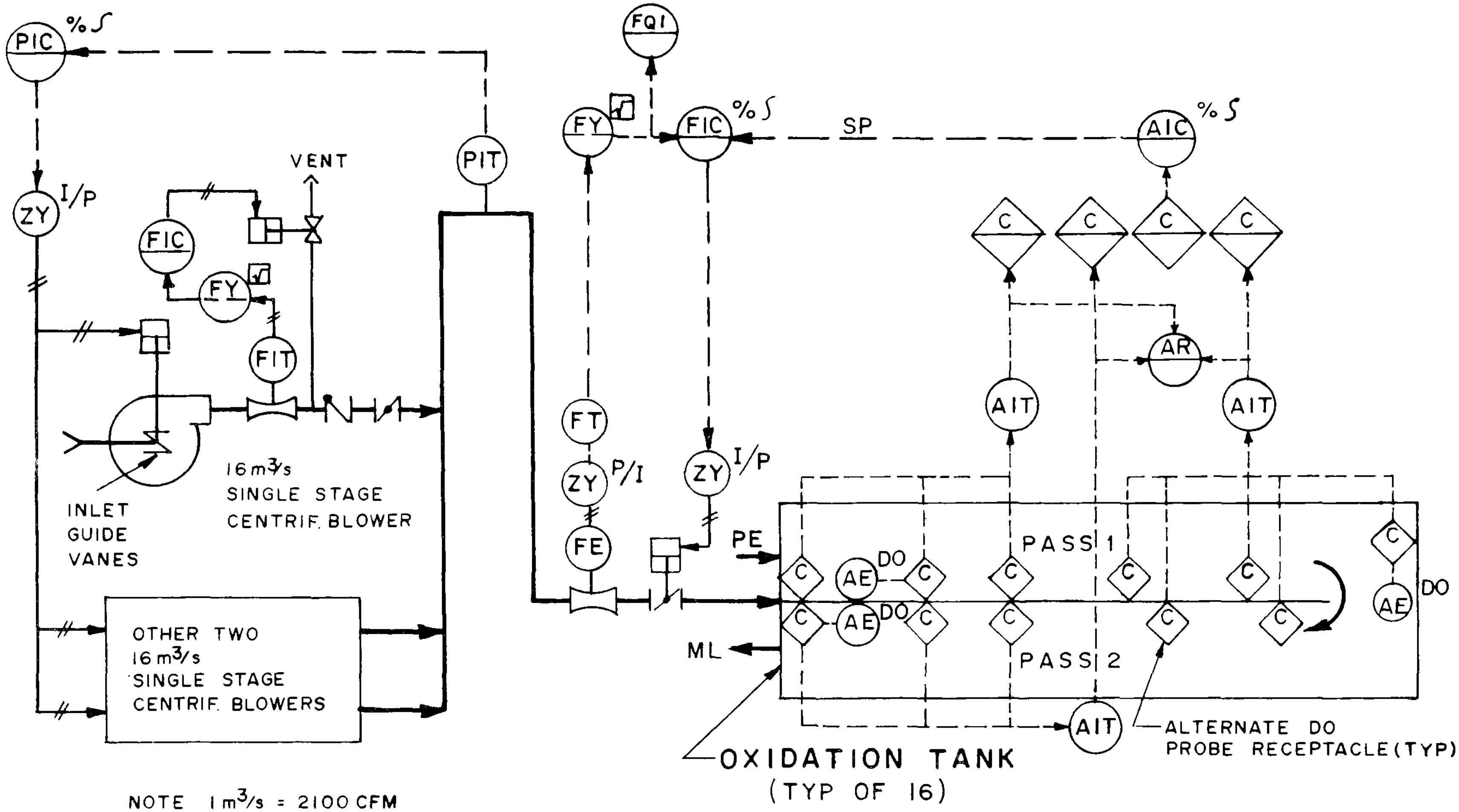


Figure 69. Automatic DO control system for diffused air $4.4\ m^3/s$ (100 mgd) activated sludge plant.

For the purpose of identifying the incremental costs of adding automatic DO control equipment to manually controlled hypothetical plants, the following definitions of manual and automatic control are employed: A manual DO control system involves the use of a portable DO probe or a laboratory analysis, such as the Winkler method, to obtain DO levels in the mixed liquor. Aeration system final control elements are manually started, stopped and adjusted from a central plant control room. An automatic DO control system involves the use of in situ DO probes for the automatic, continuous measurement and centralized display of DO levels in the mixed liquor. Automatic controllers are provided in a central plant control room for starting, stopping, and adjusting all aeration system final control elements.

Both manual and automatic DO control systems include monitoring and protective devices for the aeration equipment. Local manual controls are provided for maintenance purposes.

CAPITAL COSTS

Specific components unique to automatic DO control systems that can be identified by type and quantity are listed in Table 10. Because the combined cost of the DO probes and transmitters represents a substantial part of the total installed cost of automatic DO components for each plant, the oxidation tank configuration has a significant effect on the capital cost of DO equipment. Different numbers of tanks and passes and different tank dimensions result in either more or fewer DO probes and transmitters, thereby affecting the total capital cost of the DO control system components. Capital costs and operating and maintenance costs discussed below are based on mid-1975 prices.

OPERATING AND MAINTENANCE COSTS

Operating cost considerations include control and instrumentation equipment maintenance costs, savings in manual labor, and power savings through DO automatic control. DO probe maintenance typically involves checking, cleaning, calibration, membrane replacement, and recharging. Usually this maintenance is performed by the plant staff. More complex instrumentation maintenance is normally done by an instrumentation maintenance contractor.

The extent of in-plant maintenance required is a function of many variables, such as type of probe, capacity of electrolyte reservoir, type of wastewater, probe placement, preventive maintenance schedules, ease of probe access, and competence of maintenance personnel. DO probe maintenance schedules and manpower requirements for the case history plants described in the Appendix were analyzed, and the result reported in terms of man-hours per probe per year. Man-hours expended range from a low of 7 mh/probe/year at Oxford and Renton to a high of 64-68 mh/probe/year at the Valley and Simi Valley plants. Obviously, maintenance requirements vary

TABLE 10. INSTALLED COST OF COMPONENTS UNIQUE TO AUTOMATIC DISSOLVED OXYGEN CONTROL SYSTEMS

Components[a]	Unit installed cost-$[b]	Plant size and aeration type										Remarks
		44 dm^3/s mechanical		44 dm^3/s diffused		440 $dm^3/$ diffused		2200 dm^3/s diffused		4400 dm^3/s diffused		
		#	Installed cost-$	#	Installed cost-$	#	Installed cost-$	#	Installed cost-$	#	Installed cost-$	
DO probe	1300	2	2,600	2	2,600	6	7,800	24	31,200	48	62,400	Includes agitator, receptacle & hardware
DO probe receptacle	200	4	800	3	600	14	2,800	80	16,000	128	25,600	Extra junction box
DO indicating transmitter	1400	2	2,800	2	2,800	8	8,400	24	33,600	48	67,200	
DO recorder	1200	1	1,200	1	1,200	2	2,400	8	9,600	16	19,200	
DO indicating controller	1600							16	25,600	16	25,600	2-mode
Flow indicating controller	1600							16	25,600	16	25,600	2-mode
I/P converter	400							16	6,400	16	6,400	
DO 2-speed controller	400	2	800	1	400	2	800					Differential gap
Total			$8,200		$7,600		$22,400		$148,000		$232,000	

[a]All instruments electronic unless otherwise indicated.

[b]Installed cost based on October 1975 prices and includes a multiplier of 2 for wiring, calibration and installation.

Note: 1 dm^3/s = 2.28×10^{-2} mgd drastically from one plant to another. It is, therefore, difficult to assign an average labor expenditure per probe.

Experience in the United Kingdom at plants such as Basingstoke, where continuous DO monitoring is performed, has shown probe calibration is required once every four to six weeks. Probe cleaning is required only prior to calibration. Membrane and anode replacements are performed every six to nine months (19).

Considering the eight case history plants in the Appendix on which DO probe maintenance data is available, the average labor time per probe per year is 36 man-hours. Table 11 shows typical frequencies of various DO probe in-plant maintenance functions reported by staff members of the case history plants.

TABLE 11. TYPICAL FREQUENCIES OF DISSOLVED OXYGEN PROBE MAINTENANCE FUNCTIONS

DO probe maintenance function	Frequency
Checking and cleaning	2 - 7 days
Recalibration	1 4 weeks
Recharging	6 - 8 months
Membrane replacement	1 - 6 months

Dissolved Oxygen Control Instrument Maintenance

Since maintenance of the plant instrumentation systems for the case histories studied is generally done under an instrumentation contract, estimates for maintaining the components of Table 10 were solicited from instrument vendors specializing in these contracts. Table 12 details annual parts and labor costs per unit of equipment for typical instrumentation contracts. Information contained in Tables 10 and 12 was used to develop the total outside instrumentation contract costs for various plant sizes as shown in Table 13. Care was taken to ensure no overlap occurred in estimated labor and materials cost for the DO probes since certain in-plant maintenance functions are already accounted for in Table 11.

Laboratory Time Credit

It was assumed that a savings in plant laboratory time would be realized with an automatic DO control system since DO concentrations are available automatically. However, a check with some of the plants described in the Appendix, including Renton, indicated that no labor savings exists. Laboratory personnel report that additional time required for DO probe calibration offsets the time that would be required for laboratory determination of oxidation tank DO level.

TABLE 12. ESTIMATED ANNUAL INSTRUMENTATION CONTRACT PARTS AND LABOR COST FOR AUTOMATIC DISSOLVED OXYGEN CONTROL EQUIPMENT

Component	Labor (man-hours)	Labor cost-$[a]	Parts cost-$	Total parts and labor cost-$
DO probe and transmitter	7	210	85	295
Controller - 2 mode	4	120	40	160
Controller - 2 speed	3	90	25	115
Recorder	4	120	100	220
I/P converter	2	60	25	85

[a]Labor cost @ $30/man-hour.

Manual Labor Credit

Installation of automatic DO control equipment is expected to result in some savings in manual labor that is normally required in valve throttling and blower speed changes. Plant experience and the results of the performance tests reported in the Appendix indicate that without automatic control systems the valves, blowers or mixers involved in the DO control system would be checked and altered as required about every four hours. Assuming a checking and throttling operation requires one man, one minute per device, a count of the blowers, mixers and header control valves for each plant as shown in Figures 65 through 69 results in an annual labor credit that is realized by the automatic DO control system. The estimated labor credit that results from automation is given in Table 14.

Power Savings Credit

An analysis of the percent improvement in air supplied per unit quantity of BOD removed indicates that an average air and power savings of 20 percent can be realized with automatic DO control systems incorporating centrifugal blowers with adjustable inlet guide vane or suction throttling constant pressure control. Positive displacement blowers and mechanical mixers realize a power savings with automatic DO control through dual or multiple

TABLE 13. ESTIMATED INCREMENTAL ANNUAL INSTRUMENTATION CONTRACT PARTS AND LABOR COST FOR AUTOMATIC DISSOLVED OXYGEN CONTROL EQUIPMENT

Component[a]	Units parts and labor cost-$[b]	Plant size and type aeration									
		44 dm^3/s mechanical		44 dm^3/s diffused		440 dm^3/s diffused		2200 dm^3/s diffused		4400 dm^3/s diffused	
		#[c]	Cost-$	#[c]	Cost-$	#[c]	Cost-$	#[c]	Cost-$	#[c]	Cost-$
DO probe & transmitter	295	2	590	2	590	6	1,770	24	7,080	48	14,160
Controller - 2 mode	160									32	5,120
Controller - 2 speed	115	2	230	1	115	2	230	32	5,120		
Recorder	220	1	220	1	220	2	440	8	1,760	16	3,520
I/P converter	85							16	1,360	16	1,360
Total			$1,040		$925		$2,440		$15,320		$24,160

[a]Receptacles not included.

[b]Unit parts and labor cost from Table 12.

[c]Number of components from Table 10.

Note: 1 $dm^3/s = 2.28 \times 10^{-2}$ mgd.

speed operation. For the purposes of this economic analysis, a 20 percent power savings is assumed for the positive displacement blowers and mixers in the hypothetical plants if 2-speed drives are used.

TABLE 14. ESTIMATED ANNUAL LABOR CREDIT FOR AUTOMATIC DISSOLVED OXYGEN CONTROL

Hypothetical plant and aeration type	Number of blowers, mixers or valves	Man-hours per year[a]	Annual cost[b] $
44 dm^3/s mechanical	2	88	968
44 dm^3/s diffused	2	88	968
440 dm^3/s diffused	3[c]	132	1,452
2200 dm^3/s diffused	16	704	7,744
4400 dm^3/s diffused	16	704	7,744

[a] Assumes one minute/valve every 4 hours (44 man-hours per unit per year).

[b] Based on a salary of $14,000/year for a plant operator plus 50% allowance for fringe benefits ($11.00 per hour total).

[c] Assumes 1 unit each for blowers and 1/2 unit for each header throttling valve.

Note: 1 $dm^3/s = 2.28 \times 10^{-2}$ mgd

A straight line relationship was assumed between air saved and power expended. If suction throttling is employed on centrifugal blowers, a power savings is realized that is almost directly proportional to the reduction in discharge air flow. A slight reduction in blower efficiency occurs during suction throttling, but this effect was ignored in the computation of power savings.

The positive displacement blowers and mechanical mixers of the hypothetical plants realize a power savings under automatic DO control only through speed reduction. Power consumed by the St. Regis plant (Case History No. 9) 45 kW (60 hp) mixers was measured and a 30 percent power decrease was observed in dropping from high to low speed. For the purposes of this economic analysis, it is assumed a 20 percent power savings can be realized with the positive displacement blowers and mixers of the hypothetical plants if 2-speed drives are used.

The conversion from theoretical blower horsepower required to kWh consumed is made using an assumed load or demand factor of 1.0 and induction motor efficiencies ranging from 89-95 percent, depending on motor size. Power cost per kWh for each plant is derived from published information on the average power consumption of various size activated sludge plants (36), consideration of typical utility rate schedules, and Federal Power Commission data. Figure 70 is a plot of power costs derived from these sources. The Federal Power Commission data reflect average monthly cost of power for industrial users in the United States during 1973. Information on the Cincinnati Gas and Electric Company rates and the vertical dashed lines representing average plant power consumption were obtained from a recent EPA report (36). The Sacramento Utility District costs for selected power consumption rates were computed from the May 1, 1974 rate schedule for large industrial users (33). The synthesized curve of power costs used in this study was developed from consideration of the rate plots for the two typical utilities and the more general Federal Power Commission data. Table 15 shows estimated plant power consumption after Smith (36) and power cost per kWh read from the synthesized curve. Table 16 summarizes the operating and maintenance costs for all size plants considered.

TABLE 15. ESTIMATED ANNUAL PLANT POWER COST

Plant size, m^3/s	Average power consumption (kilowatt hours/month)	Power cost (cents/kilowatt hour)
44	35,000	3.0
440	273,800	2.4
2200	1,277,500	2.3
4400	2,585,000	2.3

Note: 1 $dm^3/s = 2.28\ 10^{-2}$ mgd.

SUMMARY OF CAPITAL, OPERATING AND MAINTENANCE COSTS

Table 17 is a combination of Tables 10 and 16 and summarizes the economics of adding automatic DO control to various size activated sludge plants on an annual cost basis. The annual capital recovery cost was computed using an interest rate of seven percent and a service life of 12 years for instruments and controls as recommended in Reference 8. Inflation of electric power, labor and equipment costs was not considered since the costs involved

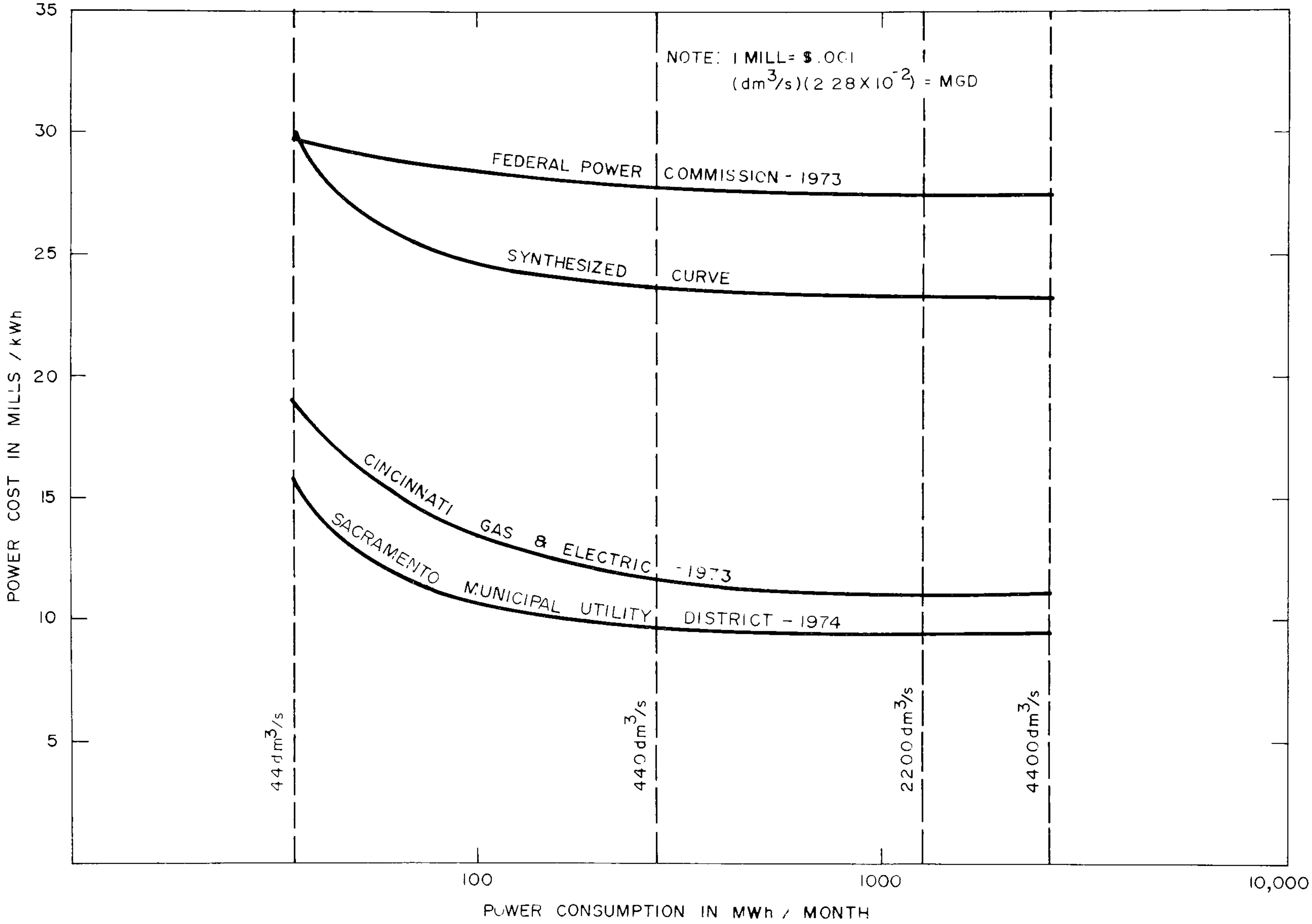


Figure 70. Average U.S. industrial power cost per kWh compared to industrial rates of typical utilities.

TABLE 16. ESTIMATED 1975 OPERATING AND MAINTENANCE COSTS OF ADDING AUTOMATIC DISSOLVED OXYGEN CONTROL TO VARIOUS SIZE ACTIVATED SLUDGE PLANTS

Item	Annual cost in dollars for various sized plants and type aeration				
	44 dm^3/s mechanical	44 dm^3/s diffused	440 dm^3/s diffused	2200 dm^3/s diffused	4400 dm^3/s diffused
DO probe maintenance @ $11.00/hour and 36 man-hours/probe/year[a,b]	800	800	2,400	9,500	19,000
DO control instrument maintenance including parts and labor[c]	1,000	900	2,400	15,300	24,200
Credit for valve modulation, blower or mixer speed change @ $11.00/hour and 44 man-hours/unit/year[d]	(1,000)	(1,000)	(1,500)[f]	(7,700)	(7,700)
Credit for power saved[e]	(4,400)	(1,700)	(11,000)	(52,000)	(101,000)
Total annual credit	(3,600)	(1,000)	(7,700)	(34,900)	(65,500)

[a] Based on a basic salary of $14,000/year for an instrument technician or plant operator plus 50% additional for fringe benefits.

[b] Probe maintenance includes labor for checking, cleaning, calibration, membrane replacement and recharging.

[c] Assumed under outside contract at a labor cost, including fringe benefits of $30/hour. Includes any special DO probe maintenance and all parts, See Tables 12 and 13.

[d] See Table 14.

[e] Based on a 20% reduction in air required under automatic DO control. See Table 15 for power rates used.

[f] Air header throttling valves treated as 1/2 unit each.

Note: 1 $dm^3/s = 2.28 \times 10^{-2}$ mgd.

TABLE 17. ECONOMIC ANALYSIS OF ADDING AUTOMATIC DISSOLVED OXYGEN CONTROL TO VARIOUS SIZE ACTIVATED SLUDGE PLANTS IN 1975

Item	Annual savings in dollars for various sized plants and type aeration				
	44 dm^3/s mechanical	44 dm^3/s diffused	440 dm^3/s diffused	2200 dm^3/s diffused	4400 dm^3/s diffused
Capital cost[a]	8,200	7,600	22,200	148,000	232,000
Annual capital recovery cost[b]	1,000	1,000	2,800	18,600	29,200
Annual operation and maintenance credit[c]	(3,600)	(1,000)	(7,700)	(34,900)	(65,500)
Total annual savings	(2,600)	0	(4,900)	(16,300)	(36,300)

[a] From Table 10.

[b] Based on 7% interest for a 12 year service life and no salvage value. (Capital Recovery Factor = 0.1259).

[c] From Table 16.

Note: 1 $dm^3/s = 2.28 \times 10^{-2}$ mgd.

are expected to change through time by approximately the same percentage (8). Table 17 indicates that an annual savings can be realized through automatic DO control for all of the cases shown except for the 44 dm^3/s (1 mgd) diffused air plant.

Figure 71 is plotted from the data on diffused air plants presented in Table 17 and illustrates that an annual savings in using automatic DO control can be expected for activated sludge plants larger than 44 dm^3/s (1 mgd). The conclusion is drawn that potential savings can be obtained by employing automatic DO control in activated sludge plants. It is recommended that an economic study be performed for each case in which automatic DO control is being considered. The methodology outlined in this manual is one approach to this analysis.

An intrinsic benefit of automatic DO control not treated in the economic analysis above is the improvement in plant performance parameters compared to manual DO control. It is difficult to quantify an improvement of 10-15 percent in suspended solids or BOD removal efficiencies in a plant where a conversion from manual to automatic DO control is being considered, particularly if the plant is meeting required effluent standards under manual DO control. On the other hand, an owner faced with more stringent discharge requirements that may normally necessitate expensive plant modifications should consider automatic DO control as a possible solution to the problem of improving the plant performance with a relatively small capital investment.

SIGNIFICANT COST FACTORS

A number of factors enter into the economic analysis of DO control systems that have a major impact on estimated costs. The significant cost factors identified in the preparation of this manual are: (a) blower selection, (b) number of DO probes, (c) DO probe arrangement for service, and (d) power cost.

Blower Selection

Blower selection largely determines the type of DO control system employed as well as the power credit realized under automatic DO control. Since DO probes and associated transmitters account for a major part of automatic DO control system capital costs and a substantial portion of the operating costs, careful consideration should be given to ensure that no more than the minimum number required are installed.

It has been stressed in this report that blower selection largely determines the type of DO control system employed as well as the power credit realized under automatic DO control. In general, dynamic blowers appear better suited to automatic DO control systems since horsepower can be conserved

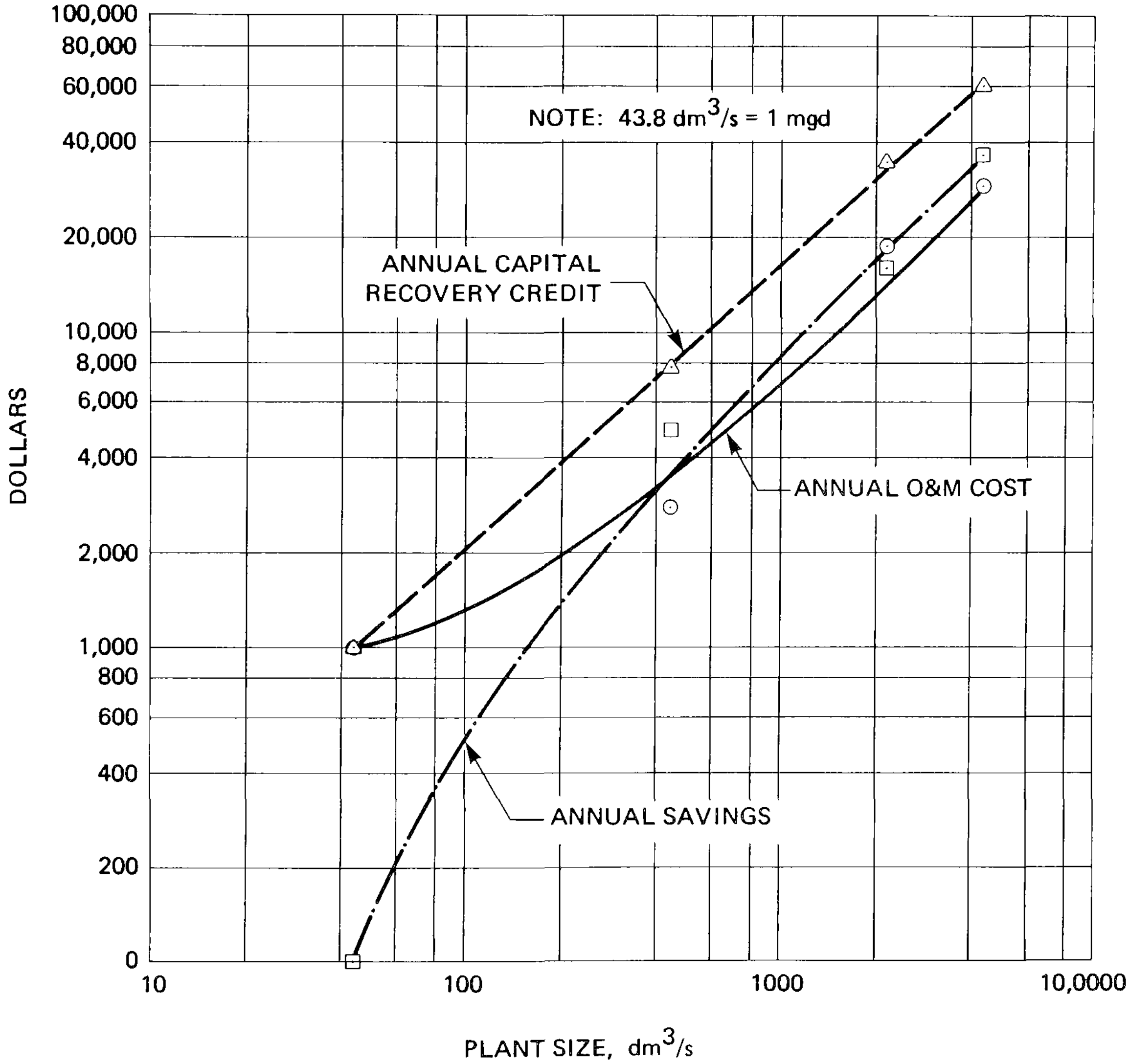


Figure 71. Automatic dissolved oxygen control economics for various size activated sludge plants.

over a variable blower operating range. Use of unloader valves or relief valves to regulate the volumetric output of positive displacement blowers does not conserve power, as discussed in Section 5. Speed variation, as observed in the field with saturated variable core reactor drives, wastes any potential power savings by expending energy through resistors when reducing blower speed.

Two-speed control systems were designed for the positive displacement (PD) blowers of the hypothetical plants. It was assumed that 20 percent power savings could be realized with this system, although not one of the case history plants had 2-speed PD blower control. Thus, power cost savings assigned to these systems is subject to question and should be further explored. One shortcoming of a 2-speed control system is that the blower output cannot closely follow the dissolved oxygen control level. It is, therefore, expected that process performance improvements would not be as pronounced with this control system as with a totally variable air flow output arrangement. A question also arises as to whether a 2-speed automatic DO control system with PD blowers will provide equivalent power savings and performance improvement as would a more sophisticated, variable range, automatic DO control system with centrifugal blowers.

Number of Dissolved Oxygen Probes

As demonstrated in Table 16, the number of DO probes utilized can make a substantial difference in the annual cost. Since such a large investment and operating and maintenance expense is involved with the DO probes and transmitters, careful consideration should be given to ensure no more than the minimum number required are installed.

Dissolved Oxygen Probe Arrangement for Service

As discussed above in the section on DO probe maintenance, a considerable difference in expended manhours per year per probe was encountered in the case history plants presented in the Appendix. DO probe in-plant maintenance may require as little as 7 mh/year per probe or as much as 66 mh/year per probe. Some of the higher and lower estimates were rechecked with the plant personnel. The Renton plant personnel attribute the relatively low requirement of 7 mh/probe/year to efficiency of maintenance and infrequency of cleaning required. The DO probes are mounted on long shafts that are pivoted on the tank railing. By pushing the short end of the shaft above the pivot, the probe is rotated out of the water parallel to the tank wall. The shaft is then dropped in a U-pipe holder and the probe is wiped clean with a rag. Calibration is done by adjusting the probe output to correspond to the oxygen content of the atmosphere (air calibration). Careful attention to probe installation design to facilitate maintenance can result in a significant reduction in man-hour requirements for keeping the probes in an effective operating condition.

Power Cost

As shown in Table 16, the major saving that can be attributed to automatic DO control is power cost. Consideration of the electric utility billing practice is an important prerequisite in determining the annual savings to a plant by installing automatic DO control equipment.

Billing systems based on maximum demand are not as favorable to automatic DO control equipment power savings as are systems based on actual energy consumed. The computation of a power credit in Table 16 is based on a utility billing system whereby a customer pays for actual energy consumed. A 93 kW (125 hp) centrifugal blower may draw 101 kW or 2424 kWh/day with a load factor of 1.0 and a motor efficiency of 92 percent when the suction throttling valve is wide open. Under automatic DO control, this same blower is expected to draw an average of 20 percent less or 1939 kWh/day. But during the course of throttling to meet the variable oxygen demand of the process, the blower will draw a variable amount of power, depending on its operating point. Under some utility billing systems, the plant is charged at a rate based on the maximum 15-minute power demand. Thus, if the blower happened to be drawing full power for 15 minutes during any given month, no amount of suction throttling to conserve power is going to affect the plant power bill charge for that blower. On the other hand, a utility billing system based on actual energy consumed is expected to result in a credit to the plant power bill of approximately 20 percent of the maximum demand if the blower is operated in an automatic DO control system. Consideration of the utility service district billing practice is thus an important prerequisite in determining a net annual cost to a plant for installing automatic DO control equipment.

The actual cost of power is also a significant factor in the economic analysis of DO control systems. For example, a 4.38 m^3/s (100 mgd) plant in Sacramento may realize $46,000 a year in savings with automatic DO control equipment, whereas the same sized plant in New York City may save $138,000. Since capital and other maintenance costs for the two plants are assumed to be the same, power cost can drastically affect the decision regarding the addition of automatic DO control equipment to a plant.

ADDITIONAL COST FACTORS

Additional cost factors that should be considered in an economic analysis of dissolved oxygen control systems are (a) process flexibility, (b) type of wastewater, (c) type of DO probes, (d) actual incremental labor costs, and (e) equipment sizing and service life.

Process Flexibility

A significant cost factor discussed above is number of probes. Number and location of probes for optional DO control are recommended in Section 6. An important consideration here is process flexibility. By having a number of probes at specified locations, the process can be switched from conventional to step feed or recycled sludge can be introduced at a different point without worrying about having a suitable DO control probe located at the proper spot for effective DO control.

Considering the demonstrated capital and maintenance cost intensiveness of DO probes, a given process application should be examined in terms of needed process flexibility and frequency of change. It appears more cost effective to use fewer DO probes and more DO probe receptacles for those processes where operating mode is changed infrequently. A reduction in DO probes utilized will have a pronounced effect on the annual cost of an automatic DO control system.

Type of Wastewater

As discussed above in DO probe maintenance, man-hours required per probe vary considerably from plant to plant. At the Valley plant (Case History No. 5), 50 percent of the total probe maintenance time is spent on probe cleaning, but cleaning is done on a daily basis. At the Oxford treatment plant, cleaning is required only once every two weeks. At the Renton, Long Beach and Simi Valley plants, cleaning is performed only once or twice per week. Assuming the probes are all subject to the same water circulation velocity and are similarly designed, it is apparent the cleaning schedule is largely a function of wastewater quality. A waste high in grease and filamentous bacteria would be expected to result in greater frequency of probe cleaning to maintain an accurate DO reading. The effectiveness of agitator assemblies in mitigating cleaning requirements is questionable since such assemblies are on all probes at the Valley plant.

Type of DO Probes

Some operators report the DO probe reservoirs are too small. With a larger reservoir, recharging the probe with electrolyte is required less frequently. Other operators report DO probe drift is excessive. One plant engineer could not understand why the aeration blowers continued to run at full capacity on an automatic DO control system, yet the tank DO concentration would not rise above 2 ppm. A check with a portable DO probe revealed the actual tank DO was 5 ppm. Some probes are reported to have a much greater propensity to drift than others, thus necessitating more frequent recalibration. The Simi Valley plant staff reports their probes have a tendency to drift to the low side.

Actual Incremental Labor Costs

DO probe in-plant maintenance cost and labor credit for valve modulation and mixer or blower speed change reported in Table 16 may not be actual costs or credits incurred on an incremental basis. A DO probe checking and cleaning operation may require five minutes. Yet with a greater number of probes in a given facility the labor cost per probe is certainly reduced. Assuming the operator has some other maintenance function to perform at the tanks or in the pipe gallery, where a throttle valve is located, it is questionable whether the calculated costs or credits are true costs or credits for automatic DO control equipment.

The superintendent of one of the plants discussed in the Appendix reported allocating a certain amount of operator time for checking DO profiles in the oxidation tanks. When asked how many man-hours per month were spent on this operation, the superintendent responded that profiles were checked only if the operator had sufficient time remaining after other duties were performed.

EFFECT OF CURRENT AND PROJECTED AVAILABILITY OF ENERGY ON VARIOUS DO CONTROL SCHEMES

An examination of Table 16 and consideration of the above section on power cost points out the significant impact of energy cost on dissolved oxygen control systems. For the smaller 44 dm^3/s (1 mgd) plants, the power savings of installing automatic DO equipment is not substantial. For the larger plants, power savings becomes so important it can offset all capital and operating costs of the automatic DO control system. The effect of current availability of energy on various DO control schemes is largely a function of the utility rate schedules and billing procedures. It has been demonstrated that an automatic DO control system is power effective. It is estimated aeration system power requirements can be reduced approximately 20 percent with automatic DO control when compared to manual DO control.

In the past, power has been abundant and inexpensive. Today and in the foreseeable future, the use of petroleum distillate or natural gas fuels is becoming increasingly expensive. Reevaluation of energy consumption and alternate energy sources are being explored. Solar power, wind power and power from solid waste are being investigated as being alternate energy sources. "Higher costs for natural gas and oil have removed these fuels from consideration for new power plants, leaving primarily nuclear power and coal to compete" (3). It is estimated that by the year 2000 almost one-half of the electrical generating capacity of the United States will be nuclear (3).

The energy needs of this country will ensure that electric power is available. Domestic energy demand has been increasing by 4-5 percent per year since 1947 (26). We are not likely to use less, but rather more power in our technologically oriented labor saving society. The differences will be in the source and the cost. The source of power does not really affect aeration air systems, but the cost does. A power cost inflation rate matching the escalation of capital goods and labor will not affect the economic analysis of DO control systems presented in this section. (Such an assumption is made in all wastewater treatment plant economic analyses in accordance with the guidelines of the Federal Register (8).) But a power cost escalation rate that outstrips other DO system costs will more greatly support a DO control system that is power effective.

Equipment Sizing and Service Life

Since the use of automatic DO control results in reduced overall air requirements for the activated sludge process, equipment sizing and service life can be reduced. For example, less costly air supply equipment (blowers, valves, piping, etc.) can be used in new plant construction if an automatic DO control system is installed. Alternatively, the service life of equipment in existing plants with manual DO control will be extended if automatic DO control is employed. As these potential savings were not included in the economic analysis, the estimated annual savings are considered to be conservative.

SECTION 9

DISSOLVED OXYGEN CONTROL SYSTEM SELECTION

The selection of a suitable DO control system for a specific plant application is a complicated process involving many considerations. The selection can be facilitated by assigning relative priorities for factors involved and then developing guidelines to aid in considering these factors.

IDENTIFICATION AND RANKING OF SELECTION FACTORS

A number of factors influencing the selection of a plant DO control system are discussed in this report. These factors are identified and ranked by degree of importance in Table 18. The ranking is offered as a general guide to the order of priorities recommended for consideration in a systematic selection of a plant DO control system. Circumstances for a particular plant may dictate that the priorities be altered.

TABLE 18. PRIORITY RANKING OF FACTORS AFFECTING CHOICE OF DISSOLVED OXYGEN CONTROL SYSTEM

Priority	Factors
1	Existing equipment or conditions
2	Capital & O&M cost
3	Energy cost
4	Reliability
5	Plant staff capability
6	Effect on plant performance
7	Flexibility
8	Adaptability to various control modes

DESCRIPTION OF FACTORS

The factors listed in Table 18 encompass many subfactors not readily apparent. An attempt was made to define the factors with a minimal amount of overlap into other factors; however, some interdependence is unavoidable.

Existing Equipment

A plant manager contemplating the addition of dissolved oxygen control equipment is certainly influenced in his consideration of available control system options by the equipment and design philosophy already present in the plant. The presence of existing equipment has the dual effect of limiting the selection of alternate DO control schemes, and of simultaneously facilitating the selection.

For example, the type of blower utilized affects the type of DO control system which may be employed. A DO control system designed around the characteristics of centrifugal blowers may not be suitable for positive displacement or axial displacement blowers.

Some plants examined for possible inclusion in the case histories described in the Appendix have the aeration air blowers committed to providing air for other uses, such as air lift return sludge pumps. Since the compressors are positive displacement machines, an automatic control system installed to conserve air output would result in the excess air being applied to the air lift pumps. This equipment design limits the options for other than manual DO control. Conversion of the compressor drives to 2-speed units may be feasible if it can be demonstrated the resultant power savings can offset the capital cost of conversion.

Flow equalization basins and other situations resulting in constant flow and loading can eliminate the need for automatic DO control. Coupled with existing equipment are existing conditions. For example, the 1.8 m^3/s (42 mgd) pulp and paper wastewater treatment plant in Pasadena, Texas, operated by the Gulf Coast Waste Disposal Authority, has eight 2-speed 112 kW (150 hp) mixers in each of two oxidation tanks. The mixer speeds can be automatically changed by a DO control system similar to that discussed in the appendix for the St. Regis plant. However, Gulf Coast operators report mixer speed change is more a function of solids suspension than dissolved oxygen concentration. Accordingly, mixer speed changes are made by the operators, as required, to keep the basin solids in suspension.

Capital, Operating and Maintenance Costs

Cost of dissolved oxygen control equipment involves capital, operating, and maintenance considerations. A decision based on capital cost alone is economically unjustified without proper consideration of all operating and maintenance costs involved.

As demonstrated in Section 8, cost analysis of DO control systems can be done on an add-on basis if it is assumed that manual DO components are common to both manual and automatic DO control systems. All contemplated automatic DO control systems can then be compared incrementally. Since service life estimates for cost-effectiveness analysis in the Federal Register (8) for structures and process equipment are much greater than for instruments and controls, a present worth cost-effective analysis over the recommended planning period of 20 years should include sufficient funds to replace the DO control equipment once.

Automatic DO control, as practiced in the field, involves selection of only one or two control probes. However, the remaining probes must still be maintained. Capital and operating cost could be significantly reduced if a plant used fewer DO probes and more alternate receptacles.

Energy Cost

The effect of various utility rate schedules on the cost of DO control systems has been discussed in Section 8. The applicable rate schedule has a direct effect on the operating cost of a DO control system. One of the first steps that should be taken in a systematic analysis of a suitable DO control system is to examine the rate structure for a particular plant in terms of energy and demand changes and see what effect a 20 percent reduction in air requirements would have on the power bill.

Figure 71 illustrates a net savings can be expected for activated sludge plants above 44 dm^3/s (1 mgd) capacity using automatic DO control. Indications are that power rates less than those shown in the synthesized curve in Figure 70 will result in a larger plant size being required before it is economical to install automatic DO control.

Utility rates and billing structures overlap into the cost factor discussed above. Neglecting process performance improvement, the key factor in deciding whether or not to install an automatic DO control system is the projected power savings. The utility should also be consulted with regard to future rate projections. Rate escalations may not necessarily keep pace with inflation of capital and maintenance costs of equipment.

Reliability

A major concern when considering various DO control scheme options is system reliability. Many plants are designed for minimal attention using sophisticated alarm and safety systems. The weakest link in an automatic DO control system is the DO probe. If sufficient plant maintenance time cannot be devoted to maintaining the probes, the DO control system will be unreliable. On the other hand, a good preventive maintenance schedule for the probes can produce consistently good results.

Plant Staff Capability

Plant staff capability refers to the caliber and training of in-plant personnel who will operate and maintain the DO control equipment. It is expected that larger treatment plants will have specialized staff members trained for efficient instrument maintenance. The prospect of adding a maintenance intensive dissolved oxygen control system to such a plant is not met with as much concern as in a smaller plant. Efficiency of DO probe maintenance will undoubtedly be higher for the larger 2.2-4.4 m^3/s (50-100 mgd) plants.

Plant staff at one facility examined during this study reported the DO control system installed was too complicated to repair without calling in the manufacturer at great expense. The equipment was, therefore, left in manual mode when the automatic control circuits failed.

Effect on Plant Performance Parameters

Automatic DO control has been demonstrated to result in an improvement in the performance parameters typically used to measure treatment efficiency. A plant staff having difficulty meeting effluent requirements may find this factor of particular importance as automatic DO control may be an alternative to more expensive treatment modifications.

Flexibility

Many activated sludge plants are now designed with multiple operating modes that require a flexible DO control system. Shifting operating modes normally results in a redistribution of the oxygen demand in the tank. Effective DO control requires selecting the proper DO control probes. Depending on the number of operating modes and the frequency of mode shift, additional DO probes and receptacles may be required.

Adaptability to Various Control Modes

Selection of a DO control system should involve consideration of existing and planned plant control modes, such as manual, local automatic and centralized automatic. The type of DO control system selected should be suited to the plant operational environment. Application of a complex DO control system would be unjustified when proper instrument maintenance is unavailable or qualified operators cannot be obtained.

Future expansion plans for the plant may involve computer control of the plant processes. It may be justifiable to install computer-auto-manual (CAM) controllers in the DO control system to permit future computer control with minimal modifications.

SELECTION GUIDELINES

Existing Activated Sludge Plants

Based on the information in this manual, managers of an existing plant with a flow capacity greater than 44 dm^3/s (1 mgd), a power rate equal to or greater than that shown in Figure 70, and having centrifugal or axial blowers for the diffused air system should consider adding automatic DO control if it is not already installed. The recommended DO control system should control blower output by discharge pressure and control air flow to the oxidation tanks by DO concentration of the mixed liquor.

Managers of an existing plant of 44 dm^3/s (1 mgd) capacity or greater and having aeration air furnished by mechanical aerators or positive displacement blowers should also consider adding automatic DO control. However, economic considerations must be carefully evaluated for plants less than 44 dm^3/s (1 mgd) capacity as the annual capital and maintenance cost of automatic DO control equipment may be greater than the annual savings in power cost. For mechanical aerators and positive displacement blowers, the system recommended is two-speed or multiple-speed control based on DO level, as described in this manual.

Managers of plants smaller than 44 dm^3/s (1 mgd) should consider automatic DO control as a means of stabilizing and improving plant performance. Cost savings may be realized with the addition of automatic DO control equipment, provided an adequate DO probe maintenance program is implemented at the plant and the probes specified have a history of successful operation in other plants.

Managers of plants with relatively constant flow and loadings should not expect to derive any benefit from installing an automatic DO control system. Also, automatic DO control is not recommended for plants with air requirements governed by maintaining solids in suspension rather than DO level, when such air flows produce a DO level in excess of that required for efficient treatment.

New Activated Sludge Plants

Designers of new plants should perform a cost-effective analysis of installing automatic DO control systems, considering the guidelines presented in this manual and the selection factors presented in Table 18. Where possible, dynamic type blowers should be utilized to provide maximum flexibility and range in DO control. Number and placement of DO probes should influence oxidation tank design to minimize the high capital and operating cost associated with these devices.

DO probes should be mounted for convenient access by maintenance personnel. A rotating shaft, pivoted on the tank handrail and having a U-bar holder similar to the Renton plant design (see Case History 1) is recommended.

Alternate prewired DO probe receptacles should be installed at locations suitable for all contemplated modes of process control.

When economic or other considerations dictate the use of positive displacement blowers or mechanical aerators, these devices should be equipped with drives that conserve power at different speeds.

Designers of plants smaller than 44 dm^3/s (1 mgd) should consider not using automatic DO control. Flow equalization basins or other flow and loading stabilizers should be investigated as alternatives for these smaller plants.

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APPENDIX

CASE HISTORIES OF DISSOLVED OXYGEN CONTROL SYSTEM PERFORMANCE, OPERATIONAL AND MAINTENANCE DATA

CONTENTS

CASE HISTORY 1

RENTON WASTEWATER TREATMENT PLANT, WASHINGTON

Description of Aeration and Dissolved Oxygen Control System

The Renton plant, located near Seattle, Washington, commenced operation in June 1965 and was enlarged in 1973 to an average dry weather flow (ADWF) capacity of 1.6 m^3/s (36 mgd). Two oxidation tanks are provided, each with four passes. Air is supplied by six single stage centrifugal blowers and introduced through two headers in each tank. Each header serves two passes.

Currently, the Renton plant is equipped with three 5.7 m^3/s (12,000 scfm), 370 kW (500 hp) blowers, and three 6.6 m^3/s (14,000 scfm), 450 kW (600 hp) blowers. All blowers are single stage centrifugal types supplied with 4160 volt power. The 370 kW (500 hp) blowers were installed in 1963 and are driven by synchronous motors. The 450 kW (600 hp) blowers were installed in 1973 and are driven by squirrel cage induction motors. All blowers are located in a temperature and humidity controlled gallery and utilize finely filtered air.

An automatic dissolved oxygen (DO) control system is provided which incorporates a pressure control loop in the blower feed manifold and a DO regulated flow control loop for each of the four tank headers. Three probes are installed in each of four passes in each oxidation tank for a total of 12 probes per tank. An instrumentation and control diagram of the DO control system is shown in Figure A-1. Components include the following:

- Single stage centrifugal blowers with individual suction throttle valves, and flow regulated surge control systems (6 ea.)
- Blower discharge manifold pressure control loop with pressure transmitter and pressure indicating controller (1 ea.)
- DO analyzers and probes (24 ea.)
- 12 point DO strip chart recorders (one recorder for each tank) (2 ea.)
- DO probe selector switches (one per air header) (4 ea.)

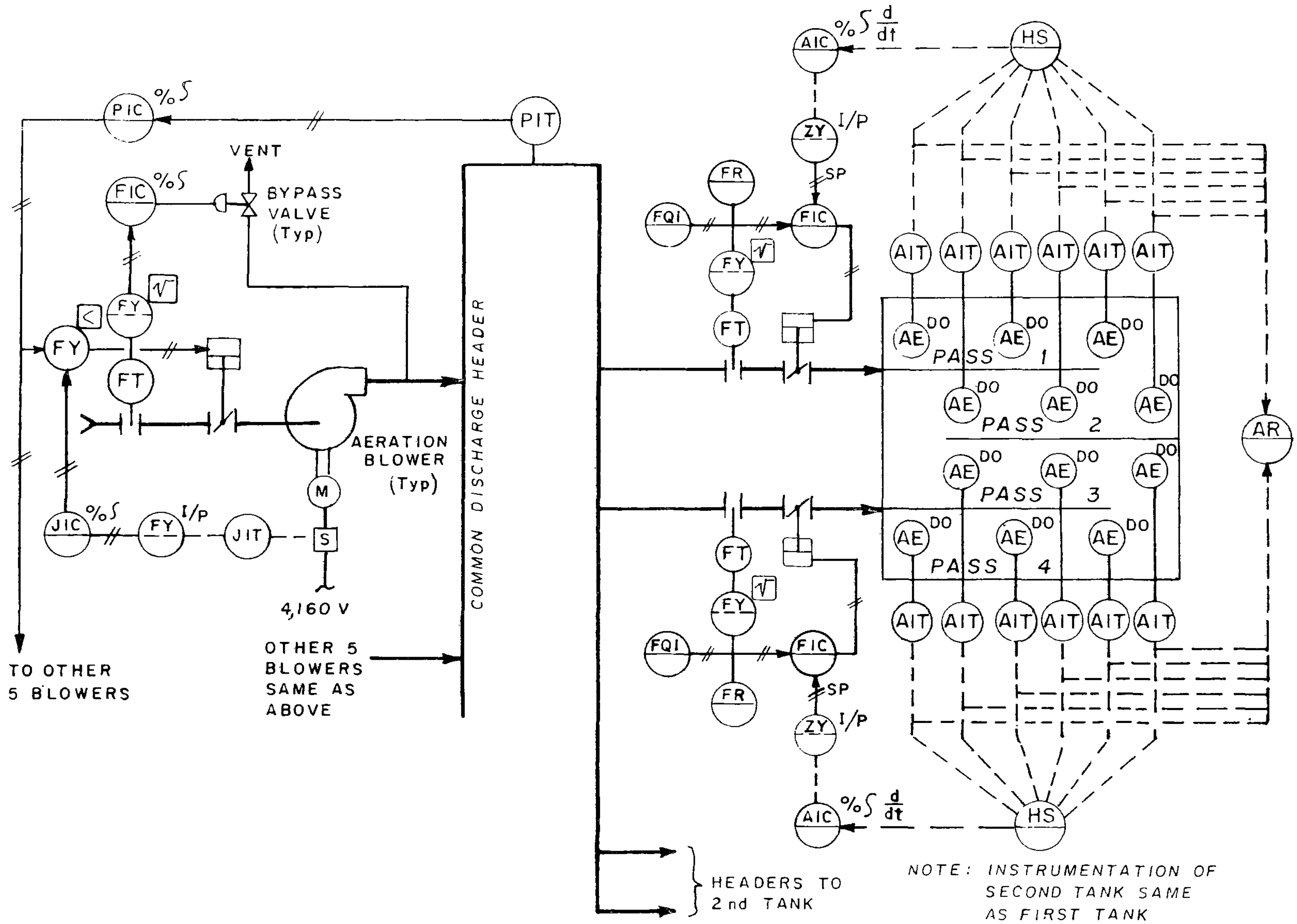


Figure A-1. Automatic dissolved oxygen control system - Renton, Washington.

- DO controllers (4 ea.)

- Flow control loops for each header, including orifice plate, square root extractor, recorder, totalizer, indicating controller and piston operated butterfly valve (4 ea.)

Operation

Currently, the Renton plant receives insufficient loading to warrant use of both oxidation tanks. However, both tanks are fully instrumented for automatic DO control. Via the appropriate probe selector switch (HS), the operator selects one DO probe in each two-pass tank section and uses that probe to control the air flow rate through the corresponding supply header. All DO probes are continuously monitored on strip chart recorder AR, and the selected control probes may be changed at any time. The output of the selected probe is transmitted to oxygen controller AIC that provides an output to vary the set point of flow controller FIC as required. The flow controller modulates a butterfly valve in the air flow header in accordance with the computed set flow rate.

The DO in the first two passes is typically maintained at 1.5 ppm utilizing one of the last two probes in the second pass for DO measurement. DO in the last two passes is usually maintained at 2-2.5 ppm using one of the last probes in the fourth pass for DO measurement.

A constant pressure of 55 kPa (8 psig) is maintained in the blower discharge manifold by simultaneously throttling all blower suction valves through a pressure indicating controller (PIC). A discharge flow regulated, surge control system with a load control override (load limit controller) is provided for each blower. If the pressure indicating controller (PIC) calls for the blower throttling valve to be open for a period of time such that the blower power draw becomes excessive, the power indicating controller (JIC) will override the pressure indicating controller and throttle the blower to a lower, less power consuming discharge rate.

Performance

The Renton plant has continuously operated under automatic DO control since 1967 with the exception of a 13 month period beginning March 1970, when the older oxidation tank was modified from a two-pass to a four-pass structure. During this period, all influent was diverted to the new oxidation tank. However, dissolved oxygen probes had not yet been installed in the new tank so DO data collection was performed by the plant laboratory. Set points on the header FIC's were determined by the laboratory using the copper sulfate-sulfamic acid flocculation modification to the Winkler test for DO. The FIC set points were varied once or twice per day according to directions from the laboratory. Other analysis performed by the laboratory included influent and effluent BOD, COD, SVI, and 30-minute settleability of the sludge. These analyses were completed once per day from 24-hour composite wastewater samples. Detailed data has been reported on three months of manual DO control in 1970 compared to the same three months of automatic DO control in 1971 (A-6).

Frequency distribution plots of BOD removal efficiency indicate that the removal efficiency was consistently high under automatic control, while efficiencies varied considerably under manual control. Data compiled on BOD removal efficiency and other performance parameters are shown in Table A-1. As indicated, the arithmetic means for SVI were 332 and 86, respectively, for manual and automatic control. This represents almost a four fold improvement by automatic DO control. However, bulking problems reported to have occurred during the manual control period would have a significant effect on SVI. Plant personnel do not attribute the occurrence of a bulking problem during the manual DO control period to use of a manual DO control system; however, the operators claim that under automatic DO control bulking is not prevalent and sludge settling and handling characteristics are better than when manual DO control is employed.

It has been reported in the literature that automatic DO control significantly reduces the air required for secondary treatment (A-2). This is confirmed by the Renton Plant data as shown on Table A-1.

Maintenance

Maintenance of the DO control system with associated blowers has been judged by the plant maintenance superintendent to require minimal labor and material costs. However, some problems have been experienced with DO probe drift and moisture accumulation in the probe plugs. At least two out of 12 probes in the operating oxidation tank have displayed excessive drift uncorrectable by recalibration. Several probes have been taken back by the manufacturer to determine the cause of the problem.

The DO probes in the operating oxidation tanks are cleaned and calibrated once a week and recharged about every eight months. Cleaning and calibration of 12 probes normally requires 1-1/2 man-hours; recharging 12 probes normally requires two man-hours. Instrument technicians performing such maintenance earn $1100-$1300 per month.

The average annual maintenance cost of each blower is approximately $1000. Of this, $500 per year per blower is spent on parts and materials and $500 per year on labor. Typical annual maintenance involves changing the oil and oil filters and inspecting the bearings. Each blower is completely overhauled every five years.

TABLE A-1. PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL AT THE RENTON WASTEWATER TREATMENT PLANT[a]

Parameter	Manual[b]	Automatic[c]	Percent improvement
BOD removal efficiency, percent[d]	85	96	11
Sludge volume index[e]	332[g]	86	74
Air supplied per unit quantity of influent,			
m^3/m^3	9.3	8.2	12
(cf/gal)	(1.2)	(1.1)	
Air supplied per unit quantity of BOD removal,[f]			
m^3/kg	137	86	37
(cf/lb)	(2190)	(1400)	
BOD removed per blower, kWh,[f,h]			
kg/kWh	0.40	0.63	58
(lb/kWh)	(0.88)	(1.4)	

[a]Data from October, November, December of 1970 and 1971.

[b]Average daily flow - 1.07 m^3/s (24.5 mgd).

Average BOD loading - 3.95 $mg/m^3/s$ (21.3 lb/1000 cf/day).

[c]Average daily flow - 1.19 m^3/s (27.1 mgd).

Average BOD loading - 5.86 $mg/m^3/s$ (31.6 lb/1000 cf/day).

[d]Geometric mean.

[e]Arithmetic mean.

[f]Average.

[g]Bulking problems occurred.

[h]Based on 15.2 $dm^3/s/kW$.

Blower maintenance is usually performed by a journeyman machinist assisted by a maintenance mechanic. The plant maintenance supervisor rates the journeyman machinist as a highly skilled mechanic and the maintenance mechanic as a semiskilled mechanic. A journeyman machinist earns $1100-$1200 per month and a maintenance mechanic earns $970-$1100 per month.

Safety and Emergency Procedures

The aeration system blowers are monitored and protected by an elaborate instrumentation and control system. The units may be started from the main plant console only when a permissive start light notifies the operator that all starting conditions have been met. The switchgear is locked out when any maintenance is being performed on a blower.

Each blower has a flow controlled surge control system and a load limit controller. A malfunction of the surge control system causes a blower shutdown by the vibration or bearing temperature monitoring system. Functioning of the load limit controller is described in the previous section on operation.

During a plant power failure, air flow to the oxidation tanks ceases as all blowers coast to a stop. Auxiliary air operated oil lube pumps supply the blowers with oil while they are slowing down. Air is supplied to the lube pump receivers through air compressors operated by an auxiliary diesel engine powered generator station.

Loss of a sensor or other control system component is not serious because of the redundancy in the design of the aeration equipment. For example, a drifting DO probe can readily be replaced by another probe for the control function.

CASE HISTORY 2

PALO ALTO WATER QUALITY CONTROL PLANT, CALIFORNIA

Description of Aeration and Dissolved Oxygen Control System

The Palo Alto Water Quality Control Plant is an activated sludge facility with a current ADWF capacity of 1.5 m^3/s (34 mgd) and an average wet weather flow (AWWF) capacity of 2.3 m^3/s (53 mgd). Four oxidation tanks are provided with piping arranged for plug flow or reaeration modes of operation. Air is supplied by three positive displacement air blowers and delivered to each oxidation tank through a sparger ring. A 37 kW (50 hp) fixed speed mechanical mixer in each tank is used to mix the rising air bubbles with the mixed liquor.

Each of the three air blowers are 224 kW (300 hp), 550 rpm wound rotor motor driven units designed to deliver 3.02 m^3/s (6400 scfm) of air at 55 kPa (8 psig). The blowers are positive displacement lobe type units installed in 1972. Two saturable core reactor variable speed drive units are used to vary the speeds of the three air blower motors. One drive unit is dedicated to one blower, while the other drive unit can be switched to either of the other blowers using transfer contactors. The blowers discharge into a common manifold that delivers air to each oxidation tank through separate 0.36 m (14-inch) risers.

A DO probe is installed in each oxidation tank halfway between the mechanical aerator units and the tank dividing wall. A portable DO probe is also available to measure DO concentrations in the tanks. An instrumentation and control diagram of the DO control system is shown in Figure A-2. Components include the following:

- Positive displacement air blowers with saturated reactor core variable speed drive (3 ea.)

- Manual flow control stations for each tank including orifice plate, flow transmitter, square root extractor, flow indicator, motor operated butterfly valve and a remote manually operated valve position controller (4 ea.)

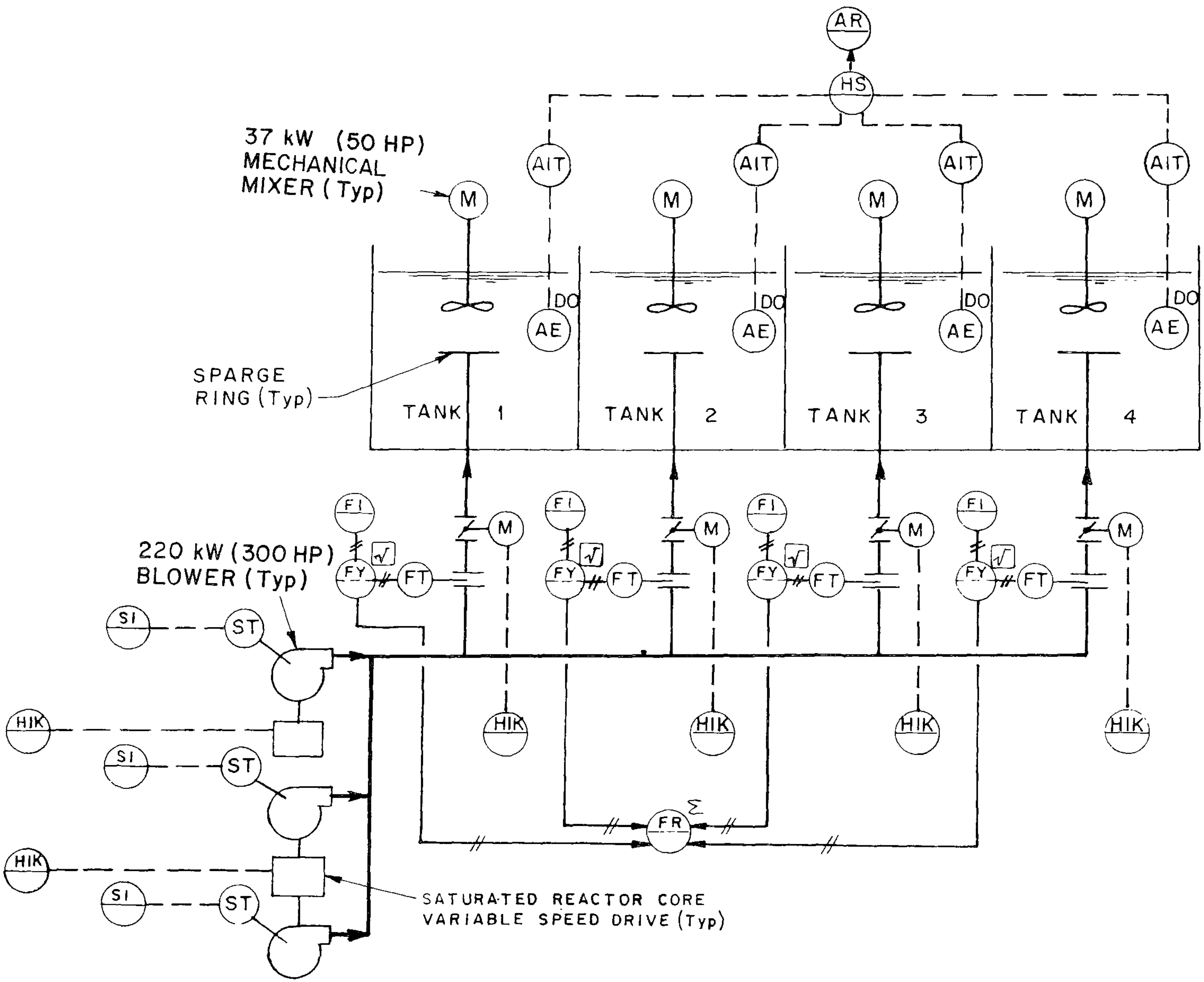


Figure A-2. Dissolved oxygen control system - Palo Alto, California.

- Flow recorder for total flow delivered to all four oxidation tanks (1 ea.)
- DO probes, agitators and analyzers (4 ea.)
- A fixed speed mechanical mixer in each oxidation tank (4 ea.)
- Single channel DO recorder with a manually operated DO probe selector switch (1 ea.)

Operation - Remote Manual

Normally, the Palo Alto plant is operated in the conventional activated sludge mode. Each oxidation tank simultaneously receives primary effluent and discharges mixed liquor to an associated final tank. Dissolved oxygen concentration in each oxidation tank is indicated on a control panel in the plant operations building. A single channel recorder may be switched from tank to tank to record the DO level.

Based on DO concentration in each tank, the operator modulates the blower motor speed on the motor operated butterfly valve in the corresponding tank air feed header. Normally, only two blowers are operating. Primary control of DO in the tanks is achieved with blower speed modulation, while secondary control is made with remote operated header feed valves. Blower speed is typically altered three times per day while the header valve positions are changed two or three times per day. The valve in the tank header farthest from the blowers is normally left wide open. Dissolved oxygen concentration in the oxidation tanks is usually maintained at 0.5-1.0 ppm.

Operation - Remote Semiautomatic

In 1973, Systems Control Inc. and the Palo Alto Water Quality Control Plant, under a grant by the EPA and the State of California Water Resources Control Board, conducted a study to compare manual vs. digital computer control of the DO control system (A-5). Following four weeks of monitoring normal control procedures in the manual mode, a digital computer system was integrated into the DO control system with a programmed DO control algorithm. The computer received a 4-20 mA DO signal from each probe analyzer, computed any changes required in blower flow rates, and typed out such changes on a teletype. A change in computed air flow rates of more than 47 dm^3/s (100 scfm) was required before a control change message was typed. Since the operator was still required to perform the blower speed change requested, this type of control is most accurately designated as computer-assisted open loop.

The DO control algorithm used in the test was an incremental, proportional plus integral, process control program designed to compute the required change in air flow rate. On occasion, such change commands required the operator to place blowers in or out of service.

The testing program at Palo Alto was divided into three stages summarized in Table A-2. During all three stages of the study, the header feed control valves were left in a fixed position.

During the first stage of approximately four weeks, the plant was operated in the remote manual mode as previously described. Blower speed was changed twice daily.

TABLE A-2. MANUAL AND SEMIAUTOMATIC DISSOLVED OXYGEN CONTROL TESTING PROGRAM AT PALO ALTO, 1973

Stage	Phase	Duration	Remarks
1	-	4 weeks	Remote manual mode of operation.
2	1	3-1/2 weeks	Infrequent data collection under remote manual mode.
	2	3 days	Frequent data collection under remote manual mode for average and extreme operating conditions.
3	1	4 weeks	Process stabilization under semiautomatic mode.
	2	3-1/2 weeks	Infrequent data collection under semiautomatic mode.
	3	3 days	Frequent data collection under semiautomatic mode for average and extreme operating conditions.

During the next stage of the study, from July 9-August 7, 1973, data was collected on plant performance for both a three and one-half week nonintensive and a 3-day intensive collection phase. The intensive period of data collection encompassed the extreme operating conditions of the plant as well as an average condition. During the intensive period, all relevant data was collected on a two-hour basis.

During the final stage of the study, the semiautomatic DO control system, as previously described, was activated. After a four-week period of process stabilization to the new control mode, intensive and nonintensive study phases of process performance were made from September 16 to October 11, 1973. Data collection phase durations for the final study step were identical to those of the previous step.

During both stage 1 and stage 2 tests, air flow applied to the oxidation tanks was totalized and BOD_5 in the primary effluent was monitored. Samples were taken from the primary effluent at four-hour intervals and combined for composite BOD_5 analysis every 24 hours.

Performance

Figures A-3 and A-4 illustrate the difference between the manual and semiautomatic DO control systems in maintaining a 1.0 ppm DO set point during the intensive testing periods. Under semiautomatic control, Figure A-4 shows the controller maintained the DO at or near set point, although substantial changes in air flow occurred due to considerable loading variation. Under manual control, wide excursions in DO concentration were experienced as shown in Figure A-3.

Average values of plant operating variables during the first and second phases of test stages 1 and 2 are shown in Table A-3. Although the percent improvements for BOD_5 and COD removal were relatively slight, suspended solids and total organic carbon percentage removal under semiautomatic DO control show a marked improvement compared to manual DO control.

Assuming a linear relationship between blower output and power consumption and a power cost of $.01/kWh, Systems Control Inc. reports power costs corresponding to the air required for each mode as shown in Table A-3. The computed annual cost savings for the automatic as compared to the manual DO control system amounts to $5400.

Maintenance

DO Probes and Analyzers--

According to the chief operator at the Palo Alto plant, DO probe calibration is typically performed once per month. During the course of the study, it was determined that preventive maintenance was required every two weeks on the probes. One man-hour was required to check all probes. Approximately once every three months, about four man-hours were required to thoroughly check, clean and recalibrate all probes. Recharging requires about 2 man-hours per year for all four probes.

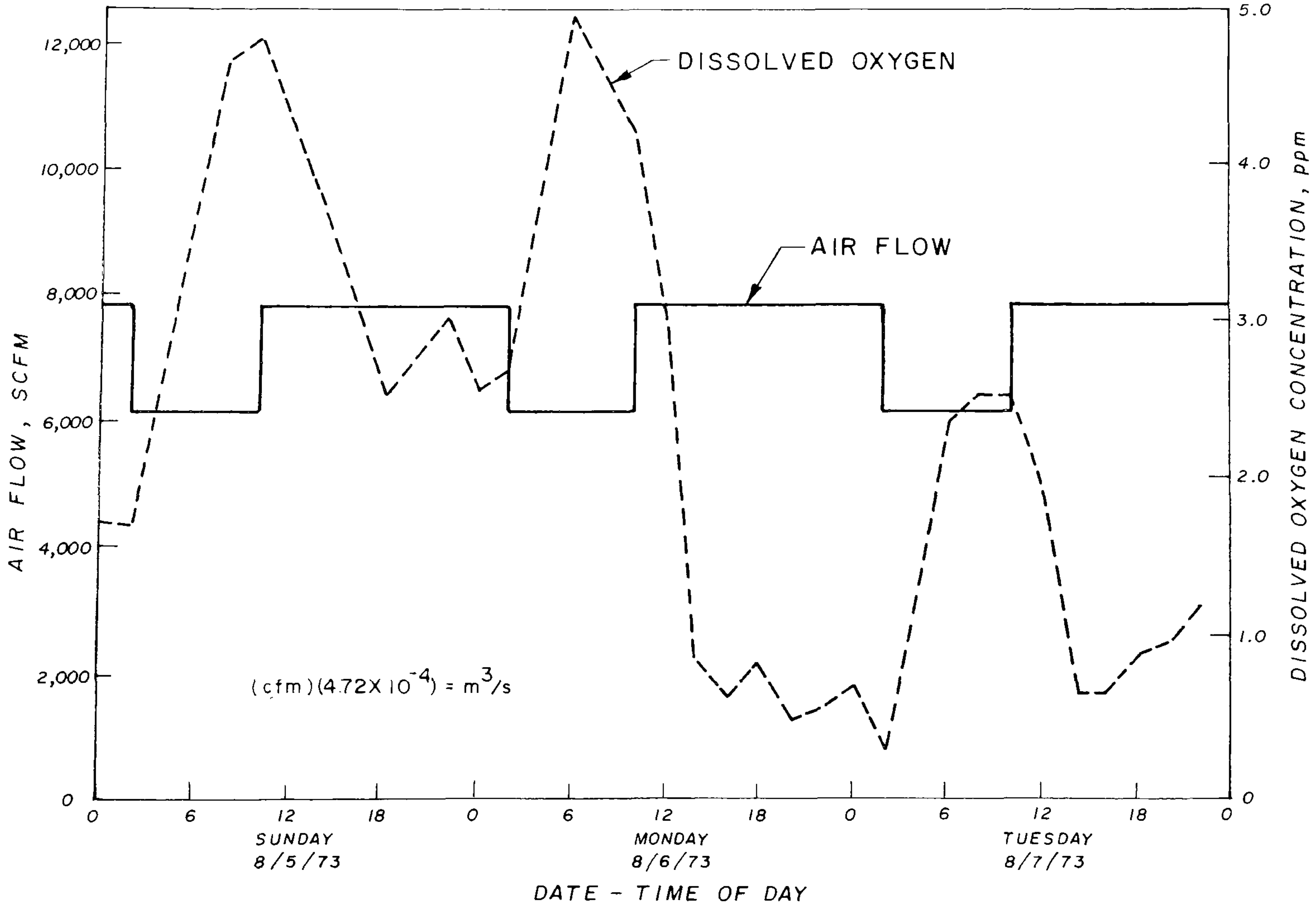


Figure A-3. Manual dissolved oxygen control - dissolved oxygen and air flow as a function of time at Palo Alto (A-5).

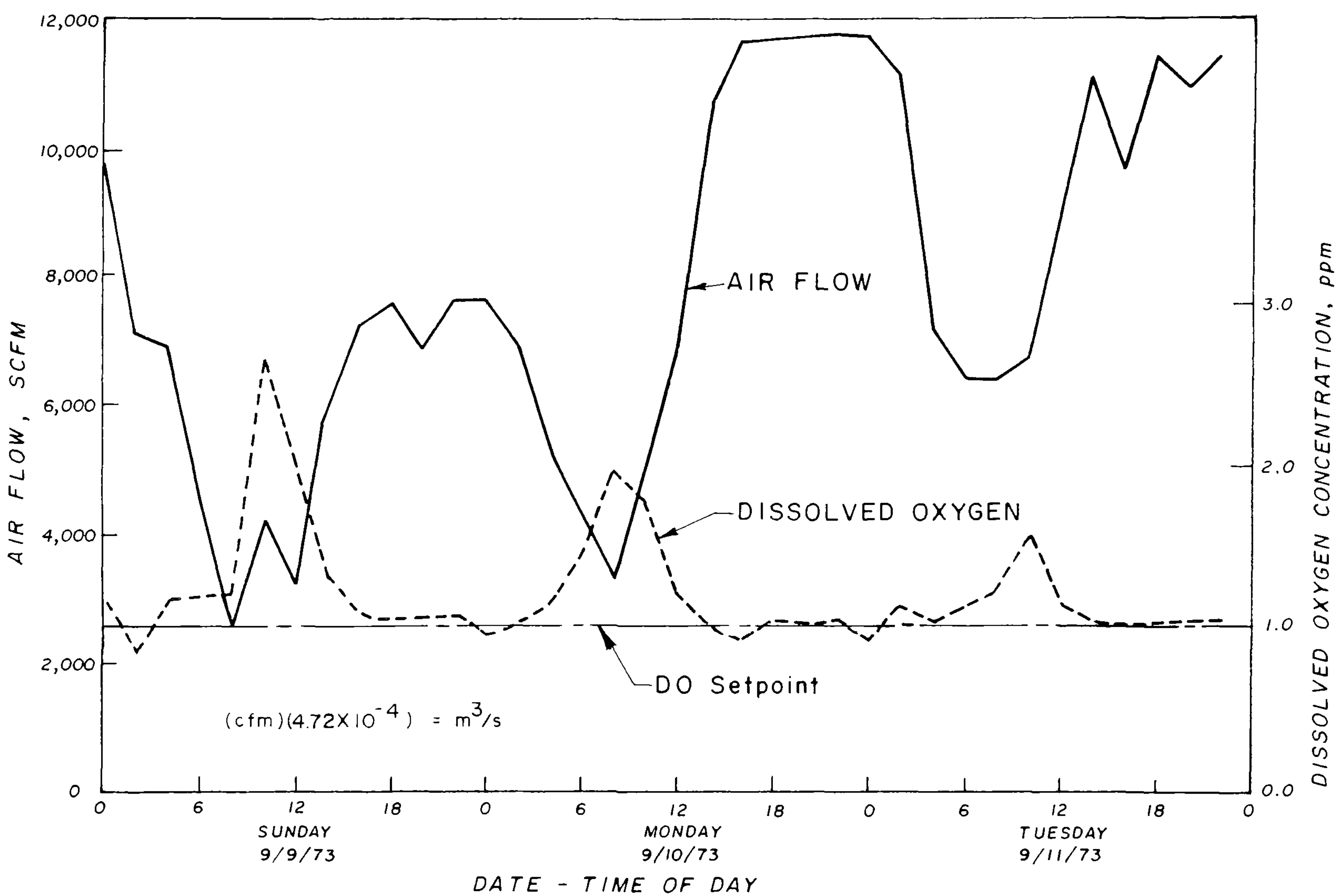


Figure A-4. Semiautomatic dissolved oxygen control - dissolved oxygen and air flow as a function of time at Palo Alto (A-5).

TABLE A-3. PERFORMANCE COMPARISON OF MANUAL AND REMOTE SEMIAUTOMATIC DISSOLVED OXYGEN CONTROL AT THE PALO ALTO WATER QUALITY CONTROL PLANT[a]

Parameter	Manual[b]	Semiautomatic[c]	Percent improvement
BOD removal efficiency, percent	84	84	none
SS removal efficiency, percent	46	53	7
TOC removal efficiency, percent	53	60	7
COD removal efficiency, percent	63	64	1
Air supplied per unit quantity of influent, m^3/m^3 (cf/gal)	3.4 (0.45)	3.4 (0.45)	none
Air supplied per unit quantity of BOD removed,[d] m^3/kg (cf/lb)	33 (520)	28 (450)	15
BOD removed per blower, kWh,[e] g/kWh (lb/kWh)	1.3 (2.9)	1.6 (3.4)	23

[a]Data from Systems Control Inc. Study, 1973. Operating mode for manual and semiautomatic was contact stabilization. Test duration was four weeks for each control mode.

[b]Average daily flow - 1.05 m^3/s (24.0 mgd).
Average BOD applied to oxidation tanks - 4.52 $mg/m^3/s$ (24.4 lb/1000 cf/day).

[c]Average daily flow - 1.03 m^3/s (23.6 mgd).
Average BOD applied to oxidation tanks - 5.23 $mg/m^3/s$ (28.2 lb/1000 cf/day).

[d]Computed from total air supplied over testing period, average BOD in primary effluent and reported BOD removal efficiency.

[e]Based on 13.5 $dm^3/s/kW$ (21.3 scfm/hp).

The DO analyzers were reported by Systems Control Inc. to produce an electrically noisy signal with inherent oscillating variation about a specific value. Electronic filtering was employed to correct this problem.

Blowers--

Blower maintenance, which is done by a mechanic earning $1090 per month, has been essentially preventive since the units were installed so recently. Every six months, all three blowers are cleaned and the oil is changed. Approximately 38 dm^3 (10 gallons) of oil are required for each blower. One man-day of labor is required for this semiannual service on all three machines.

Once per month the primary and secondary collector rings on the wound rotor motors are cleaned to remove brush deposits. Two man-hours per blower are required for this operation.

Every six months, the drive coupling bearings are cleaned and repacked. The total time required is two man-hours per blower.

Based on a labor cost of $1090 per month plus 50 percent additional for fringe benefits, the annual maintenance cost of the three blowers is estimated at $350. Special maintenance, such as overhaul, would substantially add to this cost.

Computer--

Although no problems were reported on computer downtime during the stage 3 test, the computer did fail at other times during other phases of the testing program. Over a period of about 13 months, approximately 20 computer failures were reported, of which about 50 percent would have resulted in loss of the DO controller. If the DO controller had been operating, the data loss affecting DO control would have been 49 hours. Since the computer operated continuously for about 14 months, the computer was capable of effecting automatic DO control 99.5 percent of the time.

Computer system failures occurred predominantly with the peripheral devices. The disk memory accounted for 70 percent of the total computer downtime.

Safety and Emergency Procedures

The aeration blowers are furnished with safety switches for high oil temperature, high oil pressure, low oil pressure, excessive current, and low water pressure. Activation of any of these switches will automatically shut off the blower and cause an alarm.

All blowers must be locally started. Thus, following a shutdown through an alarm condition or power failure, remote starting is not available. Loss of blowers through a power failure will effectively stop activated sludge treatment, as no auxiliary power source exists.

CASE HISTORY 3

RYE MEADS SEWAGE PURIFICATION WORKS, HERTFORDSHIRE, ENGLAND

Description of Aeration and Dissolved Oxygen Control System

The Rye Meads Works of the Middle Lee Regional Drainage Scheme, located in southeast Hertfordshire, is a tertiary treatment plant treating a dry weather flow of 0.692 m^3/s (15.8 mgd). It uses conventional primary treatment, diffused air activated sludge and sand filters and lagoons for effluent polishing. Eight oxidation tanks are provided, each with four passes. Air is supplied by thirteen lobe type, rotary, positive displacement blowers. Eleven blowers are rated at 1.6 m^3/s (3500 scfm) each, while the remaining two deliver 0.71 m^3/s (1500 scfm) each. Air is introduced through 0.18 m (7-inch) dome type diffusers. The diffusers are uniformly spaced along the base of seven tanks and distributed in a tapered pattern in the eighth tank.

The blowers discharge air at 46 kPa (6.7 psig) into a common manifold serving all eight oxidation tanks. A separate header with throttling butterfly valve is furnished for each tank pass to deliver air from the manifold to the diffusers.

The secondary process is designed to produce a fully nitrified effluent. One of the plant discharge requirements is an ammonia nitrogen concentration of less than 10 ppm at all times.

During the period July-December 1967, the Water Pollution Research Laboratory (WPRL) conducted a 6-month test of automatic dissolved oxygen control at the Rye Meads Works. Tanks 5 and 6 were selected as control units and tank 8 was used as the experimental unit. Two dissolved oxygen probes were equally divided between tanks 5 and 6.

A breadboard type of DO control system was used that involved sequential scanning and recording of all 16 DO probe outputs with preselection of four probes in tank 8 for control. The output of the four control probes was compared to four separate reference voltages corresponding to the desired oxygen concentrations. Utilizing a twin-coil relay for the butterfly valve in each of four feed headers, a 3-way, double solenoid valve was used to effect changes in pilot line pressure to a positioner on each spring opposed diaphragm valve. The valve was thereby modulated in accordance with the desired DO set point for the corresponding tank pass. An instrumentation and control diagram of the DO control system is shown in Figure A-5. Components include the following:

- Aeration blowers (13 ea.)
- DO electrode assemblies (16 ea.)
- Multipoint potentiometric recorder fitted with a retransmitting slide wire driven in synchronism with a uniselector (1 ea.)
- Twin coil relays (8 ea.)
- Double solenoid 3-way valves (4 ea.)
- Spring opposed diaphragm operated butterfly valves with positioner (4 ea.)

Operation

During the experiments at Rye Meads, tanks 5 and 6 were used as comparison tanks, and tank 8 was used as the experimental unit. Tank 7 was not operated during this time, and the remaining four tanks were not involved in the experiments.

Tank 8 was completely isolated from tanks 5 and 6 by having its own final clarifier and return sludge system. An unfortunate aspect of the experiment is that tank 8 was designed for tapered aeration, while the comparison tanks 5 and 6 had conventional aeration. Thus, judgments regarding the improvement on process performance must consider the effect of tapered aeration as well as automatic DO control in tank 8.

Performance

Performance of the activated sludge system during the study period under manual and automatic DO control is compared in Table A-4. The WPRL concluded, "using a 4-point control system, it was possible to maintain a more constant level of dissolved oxygen in the aeration tank using about 20 percent less air than in the comparison plant while still producing a high quality, fully nitrified effluent" (A-2).

An experiment was also performed at the Rye Meads Works to assess the effect of automatic DO control at higher loadings. Influent flow to tanks 5, 6 and 8 was increased 11 percent, thereby reducing the retention time to 8.5 hours. After seven weeks of operation in this mode, there was a significant deterioration in nitrification, particularly in tank 8, which was under auto-

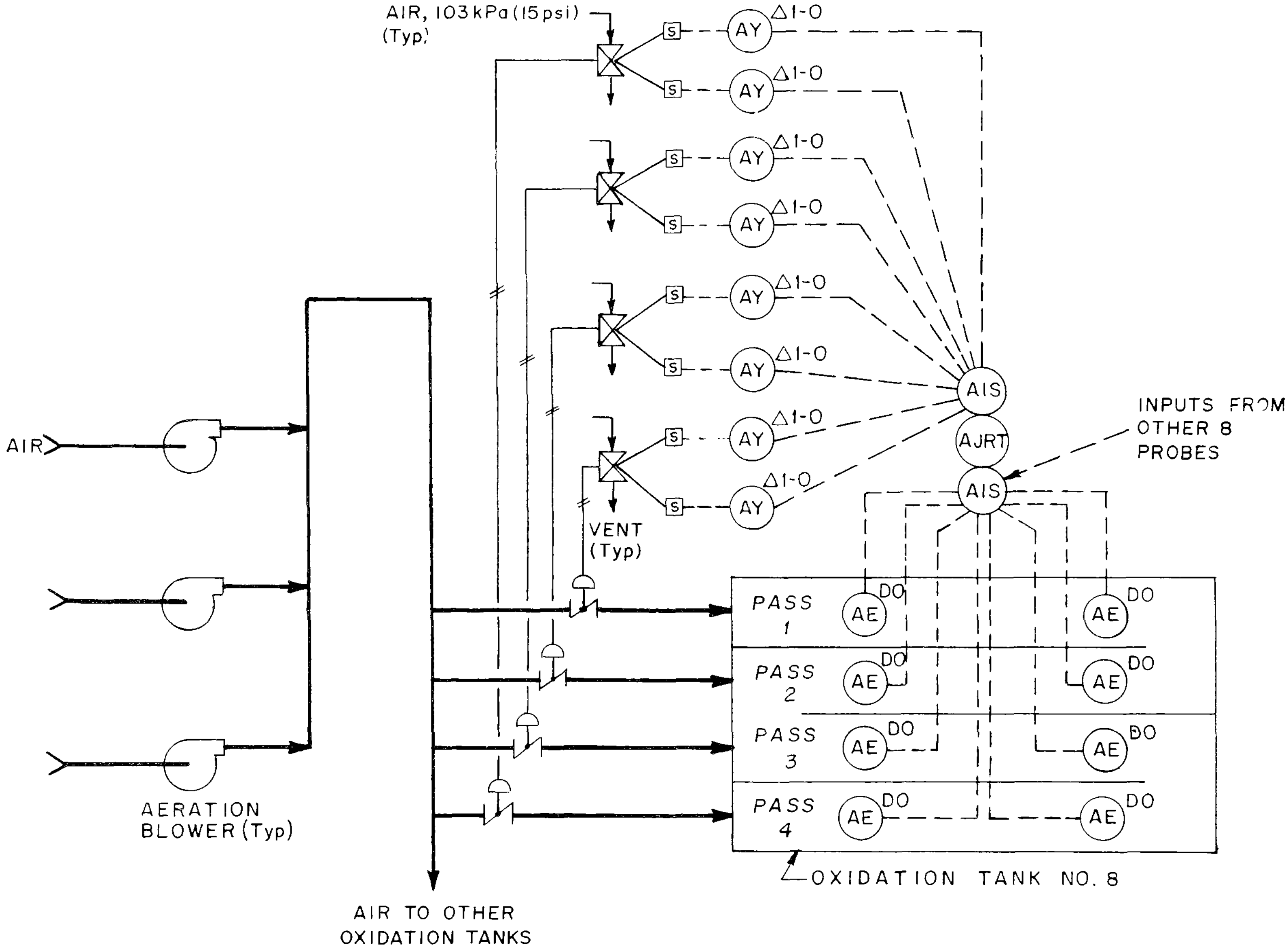


Figure A-5. Automatic dissolved oxygen control system - Rye Meads, England.

TABLE A-4. PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL AT THE RYE MEADS SEWAGE PURIFICATION WORKS[a]

Parameter	Manual[b] (tank 6)	Automatic[c] (tank 8)	Percent improvement
BOD removal efficiency, percent	97	98	1
Suspended solids removal efficiency, percent	91	92	1
Sludge volume index	45	79[d]	-76
Air supplied per unit quantity of influent, m^3/m^3 (cf/gal)	14 (1.8)	11 (1.5)	21
Air supplied per unit quantity of BOD removed, m^3/kg (cf/lb)	88 (1400)	71 (1100)	19

[a] Data from six-month study July - December, 1967.

[b] Average daily flow - 0.11 m^3/s (2.58 mgd).
Average BOD loading - 4.71 $mg/m^3/s$ (25.4 lb/1000 cf/day).

[c] Average daily flow - 0.11 m^3/s (2.48 mgd).
Average BOD loading - 4.56 $mg/m^3/s$ (24.6 lb/1000 cf/day).

[d] Higher SVI attributed to shearing action of different type return sludge pumps used on tank 8 compared to tank 6.

matic DO control. Nitrification difficulty in all three tanks was attributed to unidentified inhibitory substances.

Maintenance

Maintenance costs of the DO control system and blowers were not made available by the Laboratory Services Division of the Water Research Center.

CASE HISTORY 4

THE CITY OF OXFORD SEWAGE WORKS, ENGLAND (A-3)

Description of Aeration and Dissolved Oxygen Control System

The diffused air activated sludge plant at Oxford was started up in 1969 and the automatic DO control system was placed in operation in December 1970. Eight parallel oxidation tanks are provided, and the aeration air is supplied by two 75 kW (100 hp) variable speed blowers and one 74 kW (100 hp) fixed speed blower. Eight DO probes of the polarographic type are installed in lanes (passes) 4 and 5. The four probes in each lane are located at equal intervals.

An automatic DO control system is provided to regulate air addition to the oxidation tank to maintain a DO level of 1 ppm at the outlet end of lane 4 or 5. An instrumentation and control diagram of the DO control system is shown in Figure A-6. Components include the following:

- ° Variable speed centrifugal blowers (2 ea.)
- ° Fixed speed centrifugal blower (1 ea.)
- ° DO probes and analyzers (8 ea.)
- ° DO controller (1 ea.)

Operation

The output from each DO probe is fed to an eight-point chart recorder (AR). A selector switch (HS) is provided to select one of the DO signals as the controlled variable input to controller AIC. Usually, one of the two probes at the outlet end of the oxidation tank is used for control purposes. The output from each tank outlet probe is fed to a summing indicator (AI) fitted with high-low alarm contacts set to detect a difference of ± 0.2 ppm of DO between the two readings. The occurrence of a DO difference alarm could signify drifting or membrane failure of one of the DO probes.

The output from controller AIC is fed to the blower variable speed drive units to regulate the addition of air to the oxidation tanks. The controller is

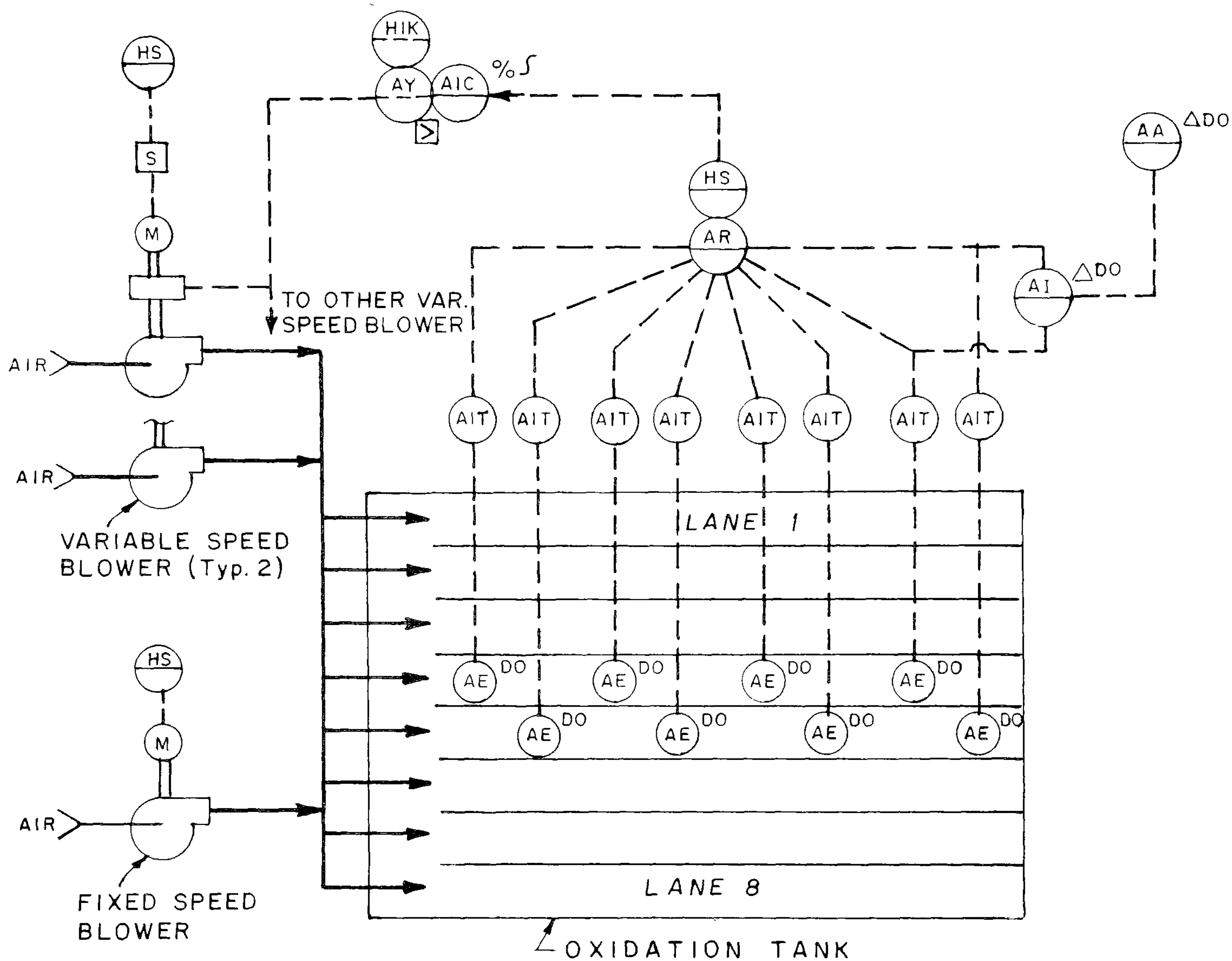


Figure A-6. Automatic dissolved oxygen control system - Oxford, England.

set to maintain a DO level of 1 ppm at the outlet end of the oxidation tanks. The minimum output signal from controller AIC is provided by regulator HIK to ensure sufficient air flow for adequate mixing of the mixed liquor even under conditions of zero loading.

Performance

Comparisons between manual and automatic DO control have been conducted at the Oxford plant. A number of experiments were conducted for periods ranging from seven days to several months. Care was taken to ensure that the periods selected for the manual and automatic control experiments provided similar plant loading conditions to permit meaningful performance comparisons.

Under manual control, the speed of the operating blowers was preset and not changed for the duration of each experiment. Under automatic control, the speed of the operating blowers was modulated to maintain a constant DO level of 1 ppm in the oxidation tanks. An average reduction in power consumption of 20 percent was achieved with the automatic DO control system.

In the opinion of the manager of the Oxford plant, the savings in power consumption through the use of automatic DO control was not the most important benefit. The main benefit was the maintenance of a healthy biomass with good settling and dewatering characteristics. However, no data were presented to support this claim.

Meredith (A-4) reports further work at Oxford established DO can be maintained at a desired level over three-quarters of a pass (lane) length if the DO probe is located one metre from the effluent weir and one metre below the water surface.

Maintenance

The DO probes are removed from the mixed liquor once every two weeks and washed with a jet of water from a portable wash bottle. Each probe is recalibrated every month. The maximum membrane life of the DO probes has been 18 months. The average membrane life has been six months.

CASE HISTORY 5

VALLEY COMMUNITY SERVICES DISTRICT WASTEWATER TREATMENT PLANT, CALIFORNIA

Description of Aeration and Dissolved Oxygen Control System

The Valley Community Services plant has an average dry weather flow (ADWF) capacity of 0.2 m^3/s (4 mgd) and has been in operation since 1961. The plant was upgraded in 1971 to provide tertiary treatment and incorporates a flow equalization basin for hydraulic load balancing. One oxidation tank is provided with several operational modes available. The operator may select conventional plug flow, step feed, contact stabilization, tapered aeration, two-pass plug flow or a combination of these activated sludge modes. The plant is normally operated in a two-pass mode with primary effluent introduced at three separate points and partial reaeration of return sludge in the head end of the first pass.

Air is supplied by three 110 kW (150 hp) and one 150 kW (200 hp) centrifugal blower, all sized to deliver 1.4 m^3/s (2900 scfm) each at a discharge pressure of 52 kPa (7.5 psig). Under actual operating conditions, the plant instruments indicate the blowers deliver approximately 1.9 m^3/s (4000 scfm) each at a discharge pressure of 31-34 kPa (4.5-5.0 psig).

Air is delivered to both oxidation tanks by a single air header, located in a trench between the tanks. Twelve separate take-offs from the header supply air to the diffusers for each tank. Each take-off has a manually controlled butterfly valve permitting adjustments for tapered aeration.

An automatic DO control system is provided which incorporates a pressure control loop in the blower feed manifold and a DO/flow cascade control loop for the oxidation tank air header. Three DO probes are provided with agitator assemblies. They are located along the outside wall of the second pass at the influent, effluent and mid-point of the tank. An instrumentation and control diagram of the DO control system is shown in Figure A-7. Components include the following:

Centrifugal blowers with individual suction throttle valves (4 ea.)

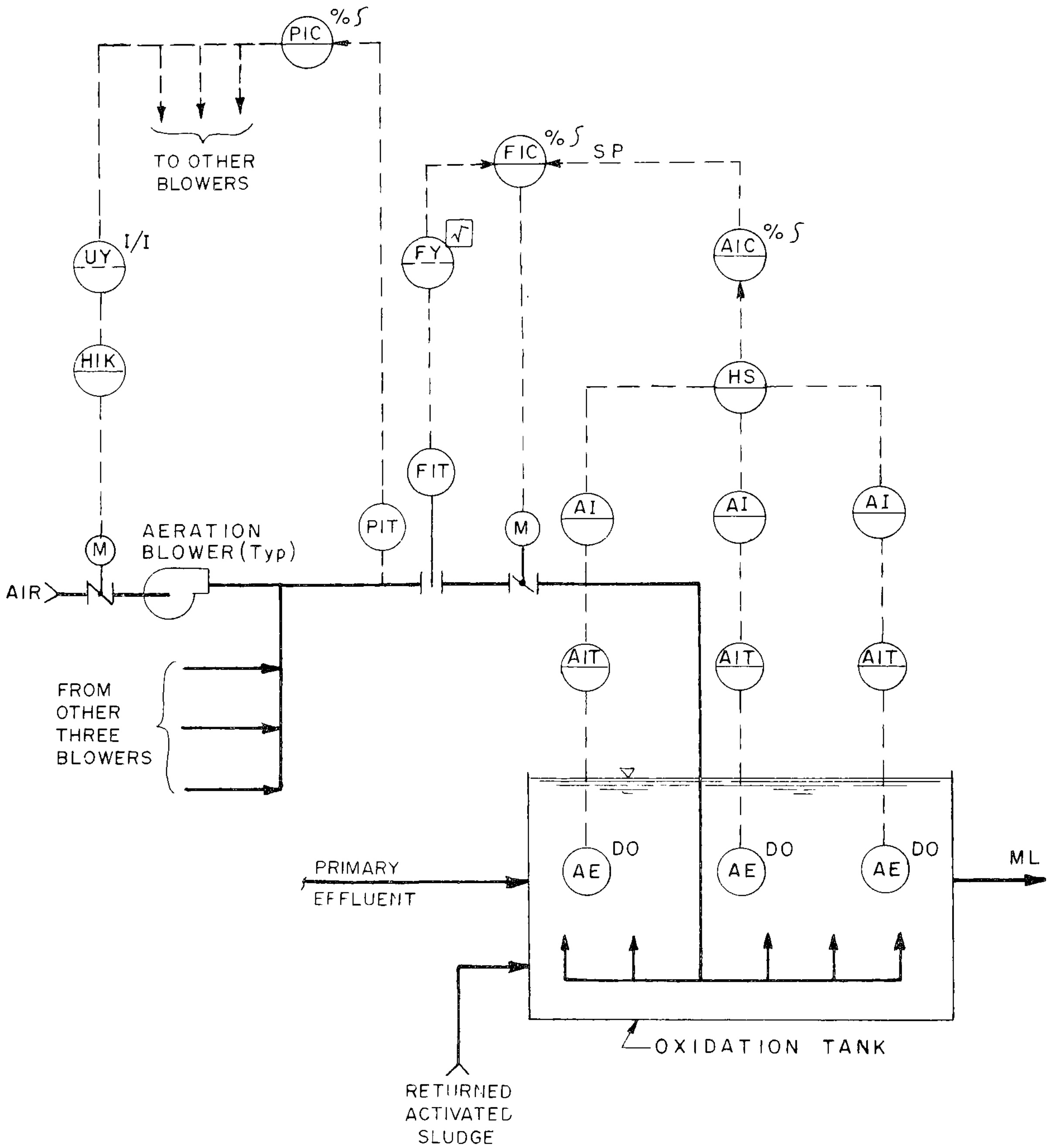


Figure A-7. Automatic dissolved oxygen control system - Valley Community Services District, California.

- Blower discharge manifold pressure control loop with pressure transmitter and pressure indicating controller (1 ea.)
- DO probes and analyzers (3 ea.)
- Air pass header flow transmitter with flow control valve and flow controller (1 ea.)
- DO controller (1 ea.)

Operation

The operator selects one of the three DO probes as the control probe via selector switch HS. The signal from the selected probe is fed to DO controller AIC; the DO set point is varied according to the mode of operation of the activated sludge process. The output of controller AIC is cascaded to the set point of flow controller FIC. The total air flow to the oxidation tank is measured by flowmeter FIT; the output of FIT is linearized by square root extractor FY and fed to the FIC as the controlled variable. The output from the FIC positions a motor-operated butterfly valve which regulates air flow to the oxidation tank.

When the plant is operated in a two-pass mode, the DO in pass No. 2 is typically maintained at 0.6 ppm for the influent probe, 1.0 ppm for the midpoint and 2.5 ppm for the effluent probe. The oxygen concentration is maintained at this level to ensure complete nitrification. Current plant effluent requirements are 10 ppm of BOD and suspended solids, less than 1.0 ppm of ammonia and zero residual chlorine. A constant pressure of 31 kPa (4.5 psig) is maintained in the blower discharge manifold by the simultaneous throttling of all blower suction valves via pressure controller PIC. Because the hydraulic load on the plant is uniform through flow equalization, the variation in air demand by the activated sludge process is not sufficient to warrant automatic starting and stopping of the aeration blowers. Likewise, automatic surge control is not provided. The only time surge control is required is during blower startup and shutdown. Thus, only manual control is employed for blower starting, stopping, sequencing and surge control.

Performance

On June 10-11, 1975, the Valley Plant staff agreed to participate in two 24-hour tests devised to compare manual vs. automatic DO control. During both tests, the plant was operated in its normal two pass mode on days selected for typical flow and loading conditions. DO control was performed using the probe located in the midpoint of the second pass since the plant had operated for an extended period of time using this probe prior to the tests. Normally, control from the last DO probe (effluent probe) is desired but this probe had been under repair for such a long time that the plant personnel had become accustomed to operating off the midpoint probe.

Under manual control, the air feed header butterfly valve was modulated as required based on hourly checks of DO concentration in the second pass. Blowers were started and stopped as required to maintain the desired DO of 2-3 ppm in the tank.

Under automatic control, the air feed header butterfly valve was automatically modulated by the DO controller (AIC) in accordance with a DO set point of 2-3 ppm for the midpoint probe. Blowers were started and stopped as for the manual test to ensure that an adequate amount of air was available. The tests were subject to a constraint that a maximum of three blowers would be permitted to run simultaneously due to power consumption considerations.

Table A-5 illustrates the results of the dissolved oxygen control study test performed on June 10-11, 1975. As indicated by the data, automatic control of DO resulted in a deterioration of virtually all parameters selected for evaluating performance. A recheck of the data verified that the calculations were correct, although the deterioration was inconsistent with test results at other plants presented in this report.

A factor that could have contributed to the performance deterioration of automatic compared to manual DO contact is blower turndown. Normally 2-1/2 blowers are needed to furnish sufficient air for the oxidation tanks, but the blowers can be throttled to only 80 percent of capacity. Plant experience has demonstrated that throttling below 80 percent results in "free wheeling" with consequent heat rise in the casing to the point where a unit drops off line. The superintendent has installed a stop on the suction throttle valve of each blower to prevent throttling below 80 percent. Thus, the automatic DO control system was constrained by blower throttling capability.

Since the plant operates with a flow equalization basin and experiences little flow or loading rate variation, it is questionable whether an automatic DO control system is necessary. Currently, the plant operates under manual DO control and the superintendent is very pleased with the quality of the effluent.

Maintenance

The centrifugal blowers at the Valley Plant have a preventive maintenance schedule as shown in Table A-6.

Plant operating personnel have experienced considerable difficulty with the DO probe connections. Apparently, these connectors are aluminum and rapidly corrode when submerged in the oxidation tank. Connector replacement

TABLE A-5. PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL OF THE VALLEY COMMUNITY SERVICES DISTRICT WASTEWATER TREATMENT PLANT[a]

Parameter	Manual[b]	Automatic[c]	Percent improvement
BOD removal efficiency, percent	94	95	1
Suspended solids removal efficiency, percent	90	87	-3
Sludge volume index	112	95	15
Air supplied per unit quantity of influent,			
m^3/m^3	24	28	-17
(cf/gal)	(3.2)	(3.7)	
Air supplied per unit quantity of BOD removed,[d]			
m^3/kg	122	162	-33
(cf/lb)	(1960)	(2590)	
BOD removed per blower, kWh,[e]			
kg/kWh	0.38	0.27	-29
(lb/kWh)	(0.85)	(0.60)	

[a] Data from 24-hour tests on June 10-11, 1975.

[b] Average daily flow - 0.176 m^3/s (4.02 mgd).

Average BOD applied to oxidation tanks - 6.80 mg/m^3/s (36.7 lb/1000 cf/day).

[c] Average daily flow - 0.154 m^3/s (3.52 mgd).

Average BOD applied to oxidation tanks - 5.19 mg/m^3/s (28.0 lb/1000 (cf/day).

[d] Computed from total air supplied over testing period and 24-hour composite BOD of primary and secondary effluent.

[e] Based on actual power consumption for blowers 1, 2 and 3 and estimate for blower 4.

involved the entire connecting lead at a cost of $50/probe. The problem was solved by fusing the connectors to the probe terminals and encasing the assembly in plastic. Probe removal from the tank now involves bringing 4.6-6.1 m (15-20 feet) of connector line back to the lab as well, but the terminal corrosion problem has been solved.

TABLE A-6. BLOWER PREVENTIVE MAINTENANCE SCHEDULE AT THE VALLEY PLANT

Item	Frequency[a]	Labor time
Lube blower bearings	Q	15 minutes
Lube motor bearings	A	15 minutes
Check blast gate setting	S	20 minutes
Repack shaft coupling	A	30 minutes
Clean unit and retouch paint	A	2 hours
Flush and lube blower and motor bearings	2 yr	1 hour
Turn lube cups one turn	M	5 minutes
Relube turn cups and turn 4 turns with caps removed	S	10 minutes
Remove, check and repack bearings	S	2 hours

[a] Q = quarterly, S = semiannually, A = annually, M = monthly

Initial experience with the DO probes indicated rubber bands and other debris consistently entered the DO probe assembly and fouled the agitator assembly. Under a recommendation from the supplier, the operating personnel placed a 3 mm (1/8 inch) mesh screen around the probe openings and effectively eliminated the fouling problem.

Probe membranes have been found to last 30-60 days. Evidence of membrane failure is usually indicated by a pronounced drift in the DO output. Membrane replacement requires less than one man-hour. DO probes are cleaned daily by washing with a hose. Approximately twice per week one man-hour is expended thoroughly cleaning and recalibrating all probes.

CASE HISTORY 6

RENO-SPARKS JOINT WATER POLLUTION CONTROL PLANT, SPARKS, NEVADA

Description of Aeration and Dissolved Oxygen Control System

The Reno-Sparks Joint Water Pollution Control Plant began operation in 1967 with an average dry weather design flow of 0.88 m^3/s (20 mgd). Currently the plant is treating an average dry weather flow of 0.83 m^3/s (19 mgd). The plant is a diffused air, activated sludge treatment facility composed of three separate treatment systems of equal capacity. Each system includes a primary settling tank, oxidation tank, final settling tank and postoxidation tank. Wastewater may be treated using conventional, three-pass, step feed, tapered aeration and contact stabilization. Digested sludge or supernatant may also be introduced into the oxidation tanks as a further process modification. Normally the oxidation tanks are operated in a three-pass mode with primary effluent and return sludge step fed in the first pass.

Diffused air for the oxidation and postoxidation tanks is furnished by three 520 kW (700 hp), 8.5 m^3/s (18,000 scfm), single stage, pedestal bearing mounted, centrifugal blowers at a discharge pressure of approximately 50 kPa (7 psig). The blowers were installed in 1966. Each blower is furnished with a diaphragm operated, flow controlled relief valve, a piston operated butterfly check valve, and a manually operated butterfly suction valve.

The blowers discharge into a common manifold with four headers; one to each of three oxidation tanks and one to the single postoxidation tank. Each oxidation tank header delivers air to an oxidation tank through two smaller headers; one for the first pass and one for both the second and third passes. Air is introduced into the mixed liquor through diffusers mounted on swing arm assemblies fitted with manually operated butterfly valves.

Air flow delivered to each oxidation tank is throttled by a flow control loop receiving a flow set point from a DO controller. Throttling the tank air feed header butterfly valves results in throttling the constant speed blowers, as the blowers react to the change in downstream pressure by restabilizing at another discharge flow rate to maintain the same discharge pressure. A flow regulated surge control system prevents blower surging by releasing the blower discharge to atmosphere when flow reaches a limiting value. An instrumentation and control diagram of the DO control system is shown in Figure A-8. Components include the following:

- Single stage, constant speed, centrifugal blowers with flow regulated surge control system (3 ea.)
- Oxidation tank and postoxidation tank supply header air flow control systems with flow tube, flow indicating transmitter, square root extractor, totalizer, flow indicating controller and piston operated butterfly valve (3 ea.)
- Dissolved oxygen probes with analyzer/transmitter (3 ea.)
- Dissolved oxygen recorders (3 ea.)
- Dissolved oxygen indicating controllers (3 ea.)

Operation

Although three blowers are provided at the Reno-Sparks plant, control circuitry is designed to permit simultaneous operation of only two blowers, thus reserving standby capacity and minimizing power costs. All blowers must be locally started. Starting and stopping a blower requires manual throttling of the blower suction valve. Blowers are normally started or stopped once or twice per day. Starter interlock circuits prevent starting a blower unless the discharge check valve is closed and the relief valve is open. Once on line, the blower suction valves are in a full open position and blower throttling is effected by automatic throttling of the piston operated butterfly valves in each air header through separate cascade flow control loops as illustrated in Figure A-8.

A DO probe (AE) is located at the end of the third pass in each oxidation tank and at the effluent end of the postoxidation tank. The output of transmitter AIT is recorded on single point recorder AR and transmitted to a DO controller (AIC). The AIC compares the input DO signal to the desired set point and decrements or increments the set point of flow controller FIC as required through a current to pneumatic converter. The FIC receives a header flow signal from flow tube transmitter FIT and throttles the header butterfly valve as required to maintain the flow set point received from the AIC. If blower discharge falls below about 3.4 m^3/s (7200 scfm) on a single blower, the surge control system will automatically bypass the flow to atmosphere.

Dissolved oxygen concentration is normally maintained at 0.4 ppm at the DO probe (AE) location in each oxidation tank. The postaeration tank DO concentration is typically maintained at 6 ppm or higher. A drawback of the automatic DO control system design is that only one throttling valve is fur-

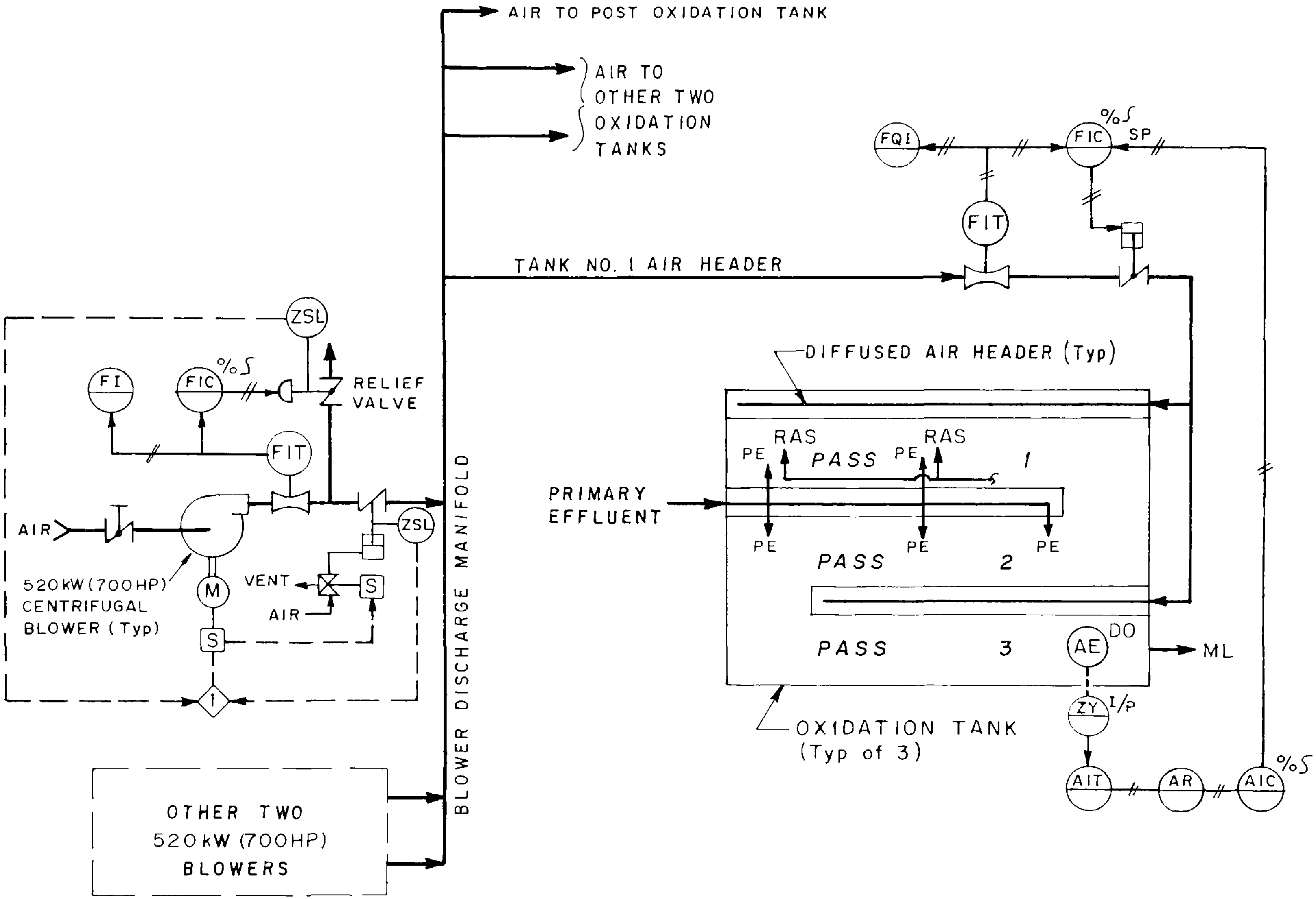


Figure A-8. Automatic dissolved oxygen control system - Reno / Sparks Joint Water Pollution Control Plant, Nevada.

nished for each system. A throttling valve and DO control loop for each header would permit close control of DO concentration in different tank passes and probably reduce air requirements. Another problem associated with the DO control system is that the System 2 influent channel is lined up with the primary effluent channel directly across the distribution channel, while Systems 1 and 3 receive primary effluent from either end of the distribution channel. As a result, the solids loading on System 2 is invariably higher than that on Systems 1 and 3.

Performance

For the purposes of this report, the City of Sparks Division Engineer agreed to run comparative tests of manual and automatic DO control on two of the treatment plant systems. Systems 2 and 3 were selected for the tests since an ongoing study was being performed in System 1. It was initially planned to run Systems 2 and 3 in parallel, with one system under manual and the other under automatic. However, due to significant differences in bacterial concentrations in each system, it was decided to run each system in alternate DO control modes so that two sets of comparative data would be available. Accordingly, two 24-hour tests were performed on each plant system August 27-28, 1975.

Under manual DO control, the butterfly valve in a system's air feed header (see Figure A-8) was manually modulated approximately every four hours to maintain a desired DO in the effluent of the third tank pass. Under automatic DO control, each system was operated as described above in the section on operation. Dissolved oxygen was maintained at approximately 0.4 ppm for both modes of operation in both systems. Table A-7 illustrates the results of the tests.

Table A-7 shows that System 3 demonstrated considerable improvement under automatic DO control for all performance parameters measured except for suspended solids removal. However, due essentially to a poor BOD removal result under automatic DO control, System 2 demonstrated marked deterioration in air supplied per unit quantity of BOD removed and BOD removed per blower kWh. This result was surprising, considering that other plants tested invariably showed improvements in the measured performance parameters under automatic DO control.

Since the reported BOD removal efficiency for System 2 under automatic DO control is so poor compared to manual DO control, it can be assumed the test was in error. Standard Methods for the Examination of Water and Wastewater reports a coefficient of variation of 17 percent in BOD data for glucose-glutamic acid mixtures. If it is assumed the BOD removal efficiency of System 2 under automatic DO control was the same as under manual DO control, applying the same plant flow rate results in the same amount of BOD

TABLE A-7. PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL AT THE RENO-SPARKS JOINT WATER POLLUTION CONTROL PLANT[a]

Parameter	System 2[b]			System 3[b]		
	Manual[c]	Auto[d]	Percent improvement	Manual[e]	Auto[f]	Percent improvement
BOD removal efficiency, percent	92	78	-14	74	85	11
Suspended solids removal efficiency, percent	83	86	3	84	82	-2
Sludge volume index	113	108	4	115	100	13
Air supplied per unit quantity of influent, m^3/m^3 (cf/gal)	10.5 (1.41)	9.5 (1.3)	10	7.1 (0.96)	5.8 (0.78)	18
Air supplied per unit quantity of BOD removed[g] m^3/kg (cf/lb)	110 (1700)	140 (2300)	-27	120 (1900)	72 (1200)	40
BOD removed per blower kWh[h] kg/kWh (lb/kWh)	0.55 (1.20)	0.29 (0.63)	-47	0.35 (0.79)	0.57 (1.2)	63

[a] Data from 4ea 24 hour tests performed on two independent activated sludge systems in same plant on August 27-28, 1975.

[b] Average daily flow - 0.28 m^3/s (6.3 mgd).

[c] Average BOD applied to oxidation tanks - 4.86 $mg/m^3/s$ (26.2 lb/1000 cf/day).

[d] Average BOD applied to oxidation tanks - 3.97 $mg/m^3/s$ (21.4 lb/1000 cf/day).

[e] Average BOD applied to oxidation tanks 3.65 $mg/m^3/s$ (19.6 lb/1000 cf day).

[f] Average BOD applied to oxidation tanks - 3.97 $mg/m^3/s$ (21.4 lb/1000 cf day).

[g] Computed from total air supplied over testing period and 24-hour composite BOD of primary and secondary effluent.

[h] Based on 16.3 $dm^3/s/kW$ (25.7 scfm/hp).

removed in each case. Considering air supplied under automatic DO control was about 9 percent less than manual, results in a 9 percent improvement in air supplied per unit quantity of BOD removed and a 10 percent improvement in BOD removed per blower kWh.

Maintenance

The dissolved oxygen control system components are maintained through a plant instrumentation contract that currently costs $19,270/year. The plant superintendent estimates about one-third of the contract time and expense is required for the DO control system, or approximately $6400 per year.

The dissolved oxygen probes, transmitters and analyzers are of the same manufacturer. Approximately 10-12 man hours per month outside of the instrumentation contract are spent cleaning and recalibrating the probes by plant personnel. Included in this maintenance is replacement of probe membranes about twice per month.

Blower maintenance, including cleaning, oil changes, lubrication, and electrical repair is estimated by the plant superintendent to require about 50 man-hours per year for all three blowers. Shortly after installation, a problem in the surge control system developed with one blower due to a faulty instrument that caused damage to the rotor, causing considerable maintenance time for repair. However, all blowers are functioning normally now, and the plant superintendent reports minimal problems with blower instrumentation systems.

Safety and Emergency Procedures

Interlock circuits prevent starting a blower unless its check valve is closed and its relief valve is open. Both valves may be operated manually as required. After a blower starts, it will shut down if the check valve fails to open within a set period of time (approximately 45 seconds) or if the bearing lubrication oil overheats or loses pressure.

Electrical interlocks also require that one blower be placed in a standby condition before either of the other blowers can be started. A blower must be stopped by normal shutdown procedure before it can be placed in a standby status.

An auxiliary oil lubrication pump is furnished for each blower to provide sufficient oil pressure during start-up and shutdown and to back up the main oil pump. Failure of the main, shaft driven oil lubrication pump during blower operation will cause automatic start-up of the auxiliary pump.

Each aeration flow controller (FIC) can be operated in manual, automatic and ESP (automatic external set point modes). The DO controllers (AIC) can be operated in manual or automatic control modes. If the automatic mode of DO controller AIC is malfunctioning or out of service, the manual mode can be used together with the ESP mode of aeration air flow controller FIC to maintain a relatively constant ratio between the aeration air flow rate and the sewage flow rate. If the ESP mode is out of service, the automatic mode of aeration air flow controller AIC can be used to maintain a desired aeration air flow rate. If the automatic mode is malfunctioning or out of service, the manual mode of aeration air flow controller AIC can be used to establish a desired flow rate. Under normal conditions DO/air flow cascade control is used as described in the previous section on operation.

The plant operating manual advises setting air flow indicating controller FIC to manual mode before removing any portion of the DO control system for maintenance or repairs. Thus, an approximate desired air flow rate can be maintained when an item such as the air flow transmitter (FIT) is taken out of service.

CASE HISTORY 7

SIMI VALLEY WATER QUALITY CONTROL PLANT, CALIFORNIA

Description of Aeration and Dissolved Oxygen Control System

The Simi Valley plant has an ADWF capacity of 0.31 m^3/s (7 mgd) and has been in operation since 1974. One oxidation tank with three passes is provided for carbonaceous oxidation and nitrification. The design permits plug flow, step feed and reaeration operating modes. Air is supplied by five centrifugal blowers; three modulating blowers, each with a maximum output of 1.79 m^3/s (3800 scfm), and two 0.94 m^3/s (2000 scfm) nonmodulating blowers.

All blowers were furnished by the same manufacturer. Two of the 112 kW (150 hp) units were initially installed in 1964 and rebuilt about seven years later, while the third was installed in 1974 under a plant expansion contract. The 56 kW (75 hp) blowers were installed in 1964. All plant blowers are driven by constant speed induction motors.

An automatic DO control system is provided which incorporates a pressure control loop to modulate the suction valves on the 1.8 m^3/s (3800 scfm) blowers to maintain a constant pressure of 41 kPa (6.0 psig) in the blower discharge manifold. Two DO probes and analyzers are provided. An instrumentation and control diagram of the DO control system is shown in Figure A-9. Components include the following:

- Centrifugal blowers with individual suction throttling valves (3 ea.)
- Nonmodulating centrifugal blowers (2 ea.)
- Blower discharge manifold pressure control loop with pressure transmitter and a pressure indicating controller (1 ea.)
- DO probes, analyzers and controllers (2 ea.)
- Flowmeter (FIT) for measurement of total aeration air flow (1 ea.)
- Air header flow control valves (2 ea.)

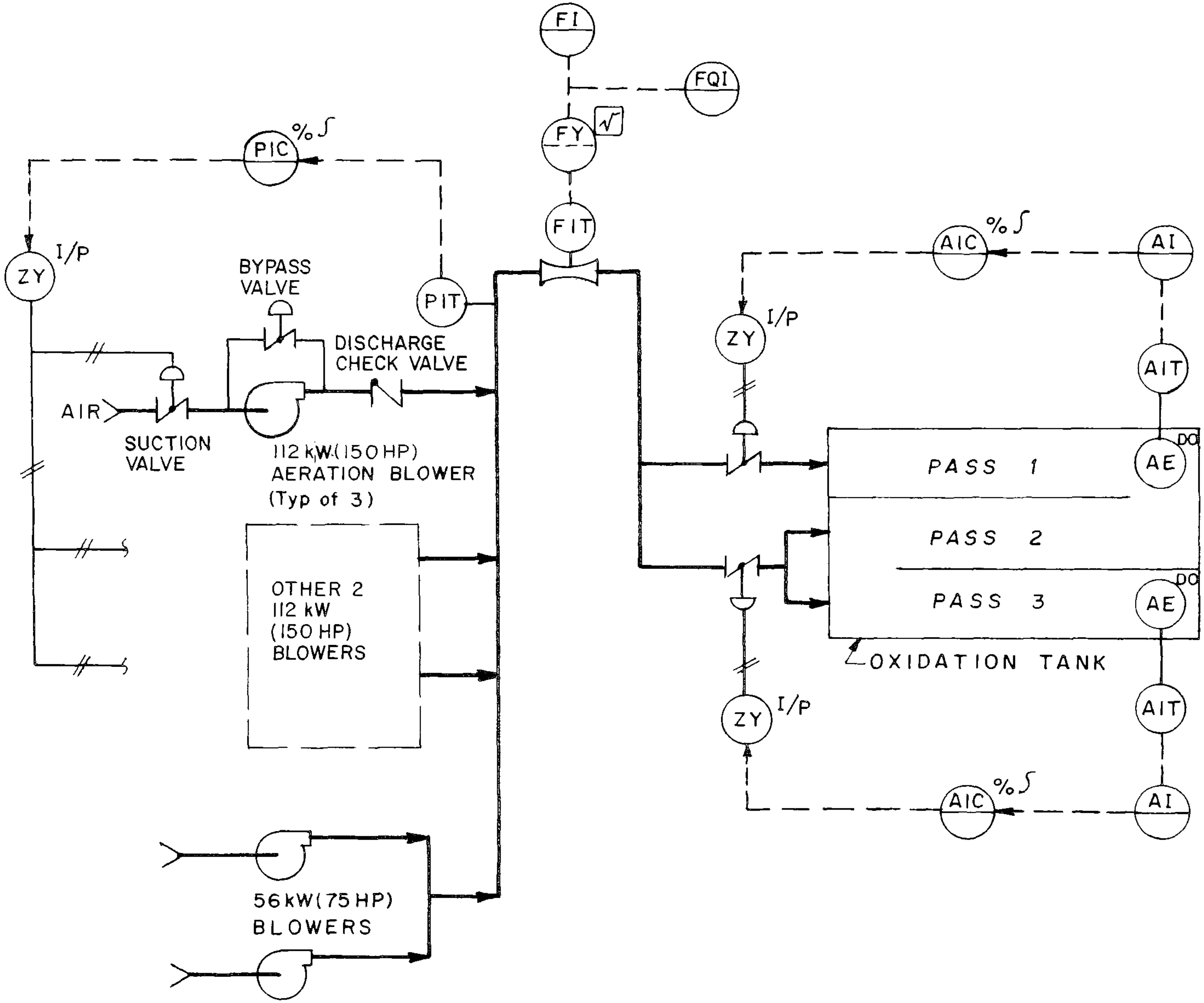


Figure A-9. Automatic dissolved oxygen control system - Simi Valley, California.

Operation

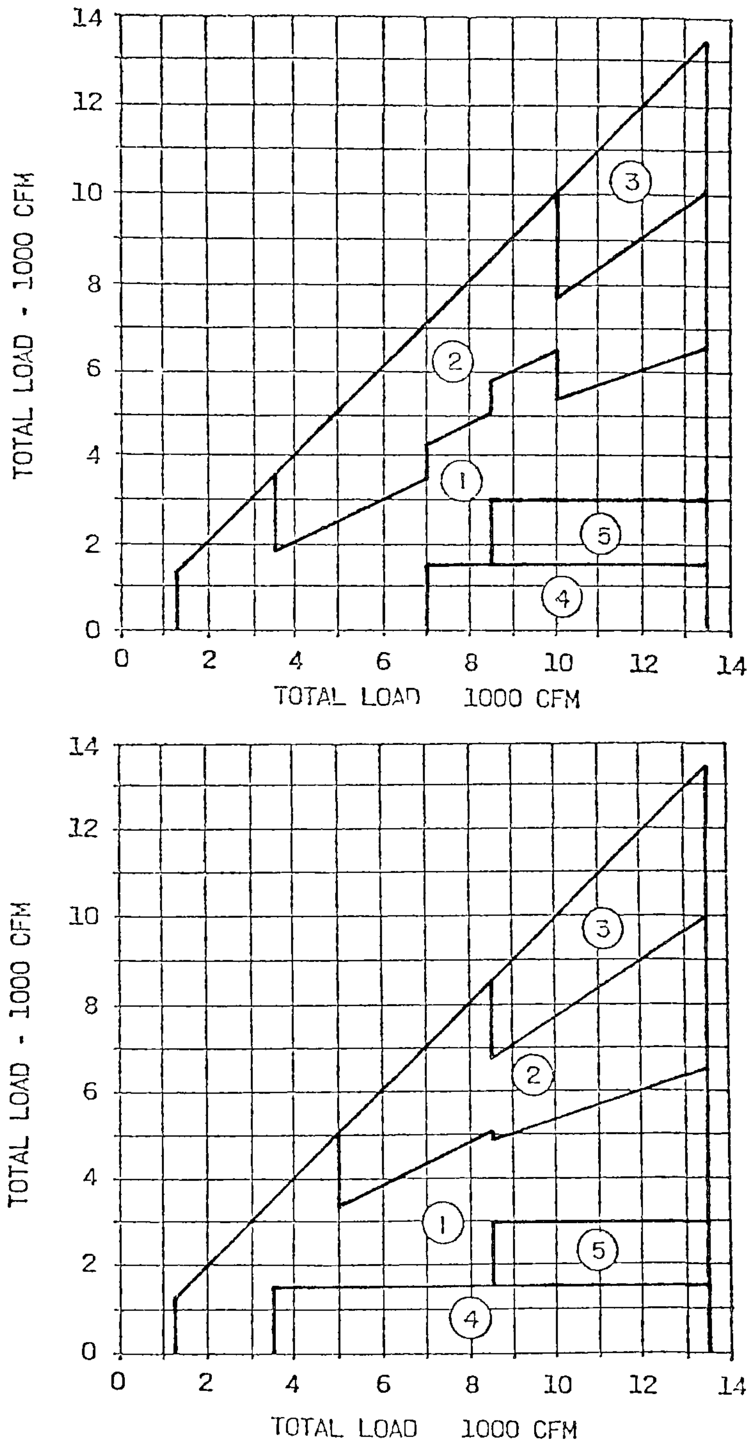
The complete blower system includes five blowers. Three are 110 kW (150 hp) and are automatically inlet choke controlled to maintain a 40 kPa (6 psig) outlet pressure, regardless of the volume requirements. The remaining two blowers are 56 kW (75 hp) and are manually operated to increase the total air capacity under peak loading conditions. The starting sequence of the 110 kW (150 hp) blowers is switch selectable on the control board in the plant control center.

Each of the 110 kW (150 hp) blowers (numbers 1,2,3) has a butterfly suction valve. All three of these valves are pneumatically actuated from a single pressure indicating controller (PIC) on the control board, based upon a desired outlet pressure in the common air header. The butterfly valves all have limit switches at both the fully open and fully closed valve positions, which are used to actuate the blower sequence control system. When the first inlet valve is fully open, the limit switch activates the motor starter relay on the second blower to bring it on line. When enough capacity is needed that both inlet valves are fully open, the third 110 kW (150 hp) blower is started automatically.

It is imperative that all blowers be operated within nominal operating ranges to eliminate the possibility of blower "surge". This condition occurs when a blower is operated at less than approximately 30 percent of full load. Due to this requirement, the starting of the manual blowers can be quite critical. If they are not started at the correct time, as indicated on Figure A-10, severe underloading of the other online blowers can occur. For example, the blower sequence diagrams indicate that blower number 4 (75 hp-manual), can either be started at 1.6 m^3/s (3500 cfm) loading or at 3.3 m^3/s (7000 cfm) loading, but should not be started at any other loading. Blower number 5 should be started at 4.0 m^3/s (8500 cfm), or higher. If this sequence is not followed, surging of online blowers is likely.

When a blower is not in service, the blower bypass valve is always open. This allows the blower to start up by recycling air back to its inlet. When the blower motor starts, it triggers a time delay relay which shuts the bypass valve after 15 seconds of blower operation. This forces open the check valve into the main air header. When power to a blower is stopped, the bypass valve immediately opens, allowing the blower to bypass air while slowing to a stop.

Total air flow is monitored in the combined air header with flow tube transmitter (FIT). The output from the FIT is linearized by square root extractor FY mounted behind the control board. Total air flow is then indicated with a 500 cm^3/s-7.1 m^3/s (1-15,000 cfm) range and totalized, with 1 count = 0.5 m^3/s (1000 cfm), on the control board. Recorder outputs are available.



NOTES: 1. Diagrams taken from plant operating manual
2. (cfm) $(4.72 \times 10^{-4}) = m^3$

Figure A-10. Blower sequence diagrams -Simi Valley Water Quality Control Plant.

Aeration air control is divided into two separate and identical systems, with each controlling the dissolved oxygen levels in a specific region of the 3-pass tank. One system controls pass 1, and the other controls passes 2 and 3.

The sensors used for dissolved oxygen measurement have a 0-5 ppm DO range. The two DO control loops can be separately controlled, with both set points individually adjustable from the control board. The reaeration DO control loop (pass 1) set point is 1.5 ppm DO, and the mixed liquor DO control loop (passes 2 and 3) set point is 3.0 ppm DO. Recorder outputs are included for both control loops.

Performance

On July 8-9, 1975, a 48-hour test was run at the Simi Valley plant to evaluate the performance of the automatic DO control system. These days were selected as average days for plant flow and loading. The test was divided into two periods of 24 hours each.

During the first 24 hours, the operators to the two automatic feed control valves in the two air headers to the oxidation tanks were disconnected. The DO control system was operated in a manual mode by reading the DO concentration on the remote indicators on an hourly basis and manually modulating the air feed header butterfly valves as required. Approximately 12 adjustments were made to the valves over the 24-hour test period.

During the second period of 24 hours, the butterfly valve operators were reconnected, and the DO control system was operated in an automatic mode as illustrated in Figure A-9. All instruments functioned normally during the test and the controllers were considered tuned.

During the tests, blowers were throttled, started or stopped as required to maintain the required manifold discharge pressure. Only two 110 kW (150 hp) blowers were used since the third unit was out of service. The 56 kW (75 hp) blowers were used to a greater extent in the manual DO control test than in the automatic test.

Dissolved oxygen was maintained close to 0.5 ppm at the end of pass 1 and close to 3.0 ppm at the end of pass 3 for both tests. The DO probes required cleaning once during each test. Results of the performance tests are presented in Table A-8. Although air supplied per unit quality of influent showed a relatively slight improvement under automatic DO control mode, other more significant parameters relative to the quantity of BOD removed demonstrated a greater improvement.

TABLE A-8. PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL AT THE SIMI VALLEY WATER QUALITY CONTROL PLANT[a]

Parameter	Manual[b]	Automatic[c]	Percent improvement
BOD removal efficiency, percent	82	81	-1
COD removal efficiency, percent	91	92	1
Suspended solids removal efficiency, percent	99	97	-2
Sludge volume index	130	127	2
Air supplied per unit quality of influent, m^3/m^3 (cf/gal)	19.8 (2.64)	19.3 (2.57)	3
Air supplied per unit quantity of BOD removed,[d] m^3/g (cf/lb)	240 (3900)	220 (3500)	8
BOD removed per blower kWh,[e] kg/kWh (lb/kWh)	0.24 (0.53)	0.27 (0.59)	13

[a] Data from 24-hour tests on June 8-10, 1975.

[b] Average daily flow - 0.204 m^3/s (4.65 mgd).
Average BOD applied to oxidation tanks - 3.11 $mg/m^3/s$ (16.8 lb/1000 cf/day.

[c] Average daily flow - 0.208 m^3/s (4.74 mgd)
Average BOD applied to oxidation tanks - 3.45 $mg/m^3/s$ (18.6 lb/1000 cf/day).

[d] Computed from total air supplied over testing period and 24-hour composite BOD of primary effluent and secondary effluent.

[e] Based on blower operating times.

Maintenance

It is estimated by the plant superintendent that blower maintenance requires an annual average of two man-hours per day, at a labor rate of $10/ hr., including fringe benefits. Included in this labor estimate are blower overhauls that are normally performed once every five years on each machine.

The dissolved oxygen probes are normally cleaned and recharged, if required, once or twice per week for a total labor time for both probes of about one man-hour per week. Approximately two man-hours per month is spent replacing DO probe membranes. Recalibration is required every two weeks for a labor time of two man-hours for two probes.

Recently, plant personnel have reported considerable difficulty with DO probe drift. Recalibration has become necessary every week. Approximately four man-hours per week are required for recalibration of both probes. The project engineer for the Simi Valley plant reports one instance where the DO control system had the blower suction throttling valves wide open to maintain the 3 ppm set point in the third pass. A test with a portable DO analyzer revealed the actual tank DO was 6 ppm, yet the probes had been recently recalibrated.

Virtually all instrumentation maintenance is performed under an outside instrumentation contract that costs $2200 per year and involves one routine service call per month. Additional labor required for special calls typically costs $700 per year for a total of $2900 per year. This contract does not include parts. No estimate was available for parts cost since the plant was only recently placed in operation.

Safety and Emergency Procedures

Each of the 110 kW (150 hp) blowers has a motor overtemperature protection system. If a blower motor overheats, it will automatically shut down the blower, and the next blower in sequence is automatically started. In addition, an interlocking circuit is included to provide starting of a backup blower if an on-line blower fails. A vibration switch is also provided on each blower that will shut down that blower in the event of excessively high vibration.

The 110 kW (150 hp) blowers are designed for automatic remote start and remote shutdown. Currently, the units may be remotely started or stopped, but the automatic remote start circuits have not been implemented. The 56 kW (75 hp) blowers can also be remotely started or stopped, but will not be automatically controlled.

Two separate feeders from different substations supply the plant with power. Loss of power through one feeder will result in automatic switchover to the alternate power source.

Critical components of the dissolved oxygen control system may be replaced from the plant spare parts inventory. During repair or replacement of certain components, the plant may be operated under manual DO control.

CASE HISTORY 8

SAN FRANCISCO INTERNATIONAL AIRPORT
WATER QUALITY CONTROL PLANT

Description of Aeration and Dissolved Oxygen Control System

The San Francisco International Airport plant started operation in 1971. It is designed for an average daily flow of 0.10 m^3/s (2.2 mgd) and currently treats an average dry weather flow of about 44 dm^3/s (1.0 mgd). The plant is a secondary treatment facility installed to treat the domestic sewage discharge from the airport. Two oxidation tanks are provided, with design permitting step feed or plug flow modes of operation.

Each oxidation tank is 18 m (60 feet) square with approximately a 3.7 m (12 foot) water depth. A fixed mechanical aerator is installed in the center of each basin. Each mixer is driven by a 30 kW (40 hp), 1730 rpm, 460 v wound rotor motor. Reduction gearing is provided, so that the mixer will rotate at a maximum speed of 47 rpm and a minimum speed of 25 rpm. The speed of each mixer can be varied by a remotely located saturated core reactor variable speed drive unit. A separate drive control unit is furnished for each mixer.

A dissolved oxygen probe is located near the influent end of the second tank, so that mixed liquor passing from the first tank to the second flows past the probe. An alternate receptacle exists for installation of the DO probe in the first tank. A DO analyzer and DO controller are located in the plant operations building proximate to the mixer variable speed drive control units. An instrumentation and control diagram of the DO control system is shown in Figure A-11. Components include the following:

- Fixed position, variable speed drive mechanical mixers (2 ea.)
- Saturated reactor core variable speed drive units for mixers (2 ea.)
- Dissolved oxygen probe (1 ea.)
- Dissolved oxygen analyzer/transmitter (1 ea.)

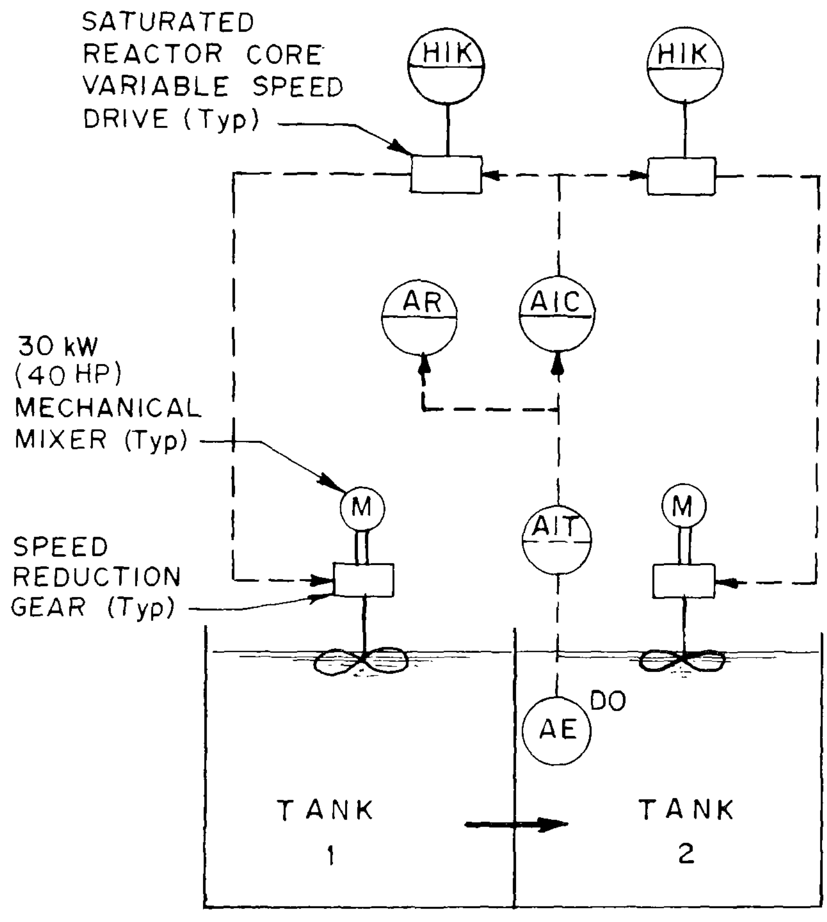


Figure A-11. Automatic dissolved oxygen control system - San Francisco International Airport, California.

- Dissolved oxygen controller (1 ea.)
- Dissolved oxygen recorder (1 ea.)

Operation

Plant operating experience indicates the two-pass mode produces a better quality effluent than operating the oxidation tanks in parallel or in series. Under parallel operation, primary effluent is not equally distributed to each tank. Under series operation, with return sludge applied to the first tank, nitrification occurs, resulting in excessive chlorine demand. Accordingly, the oxidation tanks have been operated in a two-pass mode since 1972. Under the two-pass system, primary effluent is aerated in the first tank, then applied to the second tank through a sluice gate in the common wall. The mixed liquor is then aerated with the second mixer and combined with return sludge from the final sedimentation tank.

The automatic DO control system is designed to modulate the speed of both mixers to maintain the desired DO concentration in the oxidation tanks. DO is sensed in tank 2, and the signal is transmitted to the DO analyzer (AIT) located in the rear of a remote control panel. The analyzer transmits the linearized DO level signal to controller AIC and recorder AR. The controller set point is typically set at 1.5-2.0 ppm. An error signal corresponding to the deviation above or below set point is transmitted by controller AIC to each mixer variable speed drive control unit. The drive control unit will cause the corresponding mixer to increase or decrease speed according to the error signal received from controller AIC.

Normally, the drive control unit for the mixer in tank 1 is placed in manual mode, and the mixer speed is set at 40 rpm by the manual control station (HIK). The manual control station for the second oxidation tank is normally set in automatic mode, allowing the DO controller (AIC) to vary the mixer speed from 25-47 rpm as required. Between 10 pm and 7 am, when the plant flow drops to about 30 dm^3/s (0.6 mgd), both mixers are operated in manual mode, and set at about 30 rpm. Mixers are operated at low speed at night to prevent poor mixing and bearing wear resulting from alternate revving and braking of the blades under the low water level condition. The above described "normal operation" occurred during the automatic mode reported in Table A-9.

In mid-1975, the plant was operating without automatic DO control due to failure of the same circuit relay in both saturated reactor core drive units. Under manual control, both mixers are maintained at 30 rpm from about 11 pm to 8 am. In the morning, the mixer in the first tank is set at 40-43 rpm and that in the second tank set at 47 rpm.

TABLE A-9 PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL AT THE SAN FRANCISCO INTERNATIONAL AIRPORT WATER QUALITY CONTROL PLANT[a]

Parameter	Manual[b]	Automatic[c]	Percent improvement
BOD removal efficiency, percent	92	94	2
COD removal efficiency, percent	70	84	14
Suspended solids removal efficiency, percent	79	96	17
Sludge volume index	92	201[d]	-118

[a] Data from plant records for April 1975 (automatic) and June 1975 (manual).

[b] Average daily flow - 42.9 dm^3/s (0.980 mgd).
Average BOD loading - 3.89 $mg/m^3/s$ (21.0 lb/1000 cf/day).

[c] Average daily flow - 38.0 dm^3/s (0.867 mgd).
Average BOD loading - 7.49 $mg/m^3/s$ (40.4 lb/1000 cf day).

[d] Jet fuel slug from airport received at plant.

Performance

Data collected from the San Francisco International Airport plant under manual and automatic modes of operation are presented in Table A-9. As previously explained, the automatic control mode was not operating between about 10 pm and 8 am every day. Operating experience shows that when the flowrate is 30 dm^3/s (0.6 mgd) or less, the oxidation tank water level drops too low for effective mixing by the aerators at high rpm. Thus, the mixer speed is lowered to 30 rpm in both tanks until plant flow picks up again about 8 am.

Table A-9 was compiled from data recorded over the months of April, 1975 and June, 1975 for respective operating modes of automatic and manual DO control. Improvement in plant performance is demonstrated for automatic compared to manual DO control, although the plant was in automatic mode only during the day. The high sludge volume index of 201 under automatic mode is attributed to a slug of jet fuel received at the plant. Plant records show the average COD load applied to the oxidation tanks for April, 1975 was 664 ppm, while that for June, 1975 was 323 ppm. COD and BOD removal under these conditions was surpirsingly good, even with such a high SVI.

Maintenance

Maintenance requirements of the DO control system and mechanical mixers have been relatively minor, according to the plant senior stationary engineer. However, certain parts of the saturated reactor core variable speed drive units appear difficult to obtain since in 1975 the units were out of service almost two months awaiting relays.

Preventive maintenance on the mixers involves changing or cleaning the motor brushes and changing the drive oil. Motor maintenance requires 4-6 man-hours per year per unit at a labor rate of \$10.65/hour, including fringe benefits. The mixer gear drive unit oil is changed every six months. Approximately four man-hours per year are required for oil changes at a labor rate of \$8.76/hour including fringe benefits. Each mixer requires 60 dm^3 (16 gallons) of new oil per year.

Other maintenance reported on the mixers has involved changing a motor bearing by the contractor soon after installation. This operation resulted in mixer shutdown for almost three days.

The saturated core reactor variable speed drives for the aerators require occasional adjustment. Plant records show 20-40 man-hours per year are expended adjusting and maintaining both of these units.

The dissolved oxygen probe is calibrated daily and cleaned twice per week by the plant chemist. Calibration requires less than one man-hour, while cleaning usually takes five minutes. Approximately every three months, one man-hour is spent changing the probe membrane and recharging the probe. All probe maintenance is performed by the plant chemist.

Safety and Emergency Procedures

In March, 1974, the plant was equipped with a 400 kW standby diesel generator, sized to provide full operating power for the facility. Loss of plant power causes a switchover to the auxiliary power source in less than three seconds.

The aerators are remotely started from the plant operations building. Each unit is furnished with a local lockout switch to prevent remote start when the mixer is being serviced. The drive motors are thermally protected against overload.

Presently, the plant stocks a limited number of spare parts for the automatic DO control system. Critical parts of the DO controller are on hand and may be readily installed. A spare DO probe was not available at the time of this writing in mid-1975.

Each saturated core reactor variable speed drive is electrically committed to a single aerator. Thus, loss of the variable speed drive control unit to a particular aerator would put the corresponding tank out of service. Plant operating personnel make hourly checks of DO on the remote control panel and adjust the mixer speed in tank 2 accordingly.

CASE HISTORY 9

ST. REGIS WASTEWATER TREATMENT PLANT, SARTELL, MINNESOTA

Description of Aeration and Dissolved Oxygen Control System

The St. Regis Wastewater Treatment Plant treats pulp and paper waste produced during the manufacture of paper, using the conventional activated sludge process. The plant, which went on-line in April, 1973, is designed to treat an average flow of 0.30 m^3/s (7 mgd) but currently receives about 0.20 m^3/s (5 mgd). Since paper is manufactured continuously at the paper plant, wastewater is produced 24 hours per day. Influent flow typically varies from 0.20-0.30 m^3/s (4.5-6 mgd). Two parallel oxidation tanks are provided, each with two 45 kW (60 hp) two-speed mechanical mixers driven by 460 volt induction motors. The tanks are each 30 m (100 ft) long, 18 m (60 ft) wide with a 3.7 m (12 ft) water depth. A dissolved oxygen probe with an agitator assembly is mounted near the effluent end of each tank, equidistant from the mixers. An instrumentation and control diagram of the automatic DO control system is shown in Figure A-12. Components include the following:

- Mechanical mixers (4 ea.)
- Dissolved oxygen probes with associated analyzer and transmitter (2 ea.)
- Dissolved oxygen controllers (2 ea.)
- Dissolved oxygen recorders (2 ea.)

Operation

The St. Regis plant is normally operated in an automatic DO control mode. Dissolved oxygen is sensed by a DO probe (AE) in each oxidation tank, analyzed by a panel mounted analyzer (AIT) and transmitted to DO controller (AIC) and recorder (AR). The DO controller (AIC) effects a speed change in both mixers through each motor starter in accordance with the dissolved oxygen control level.

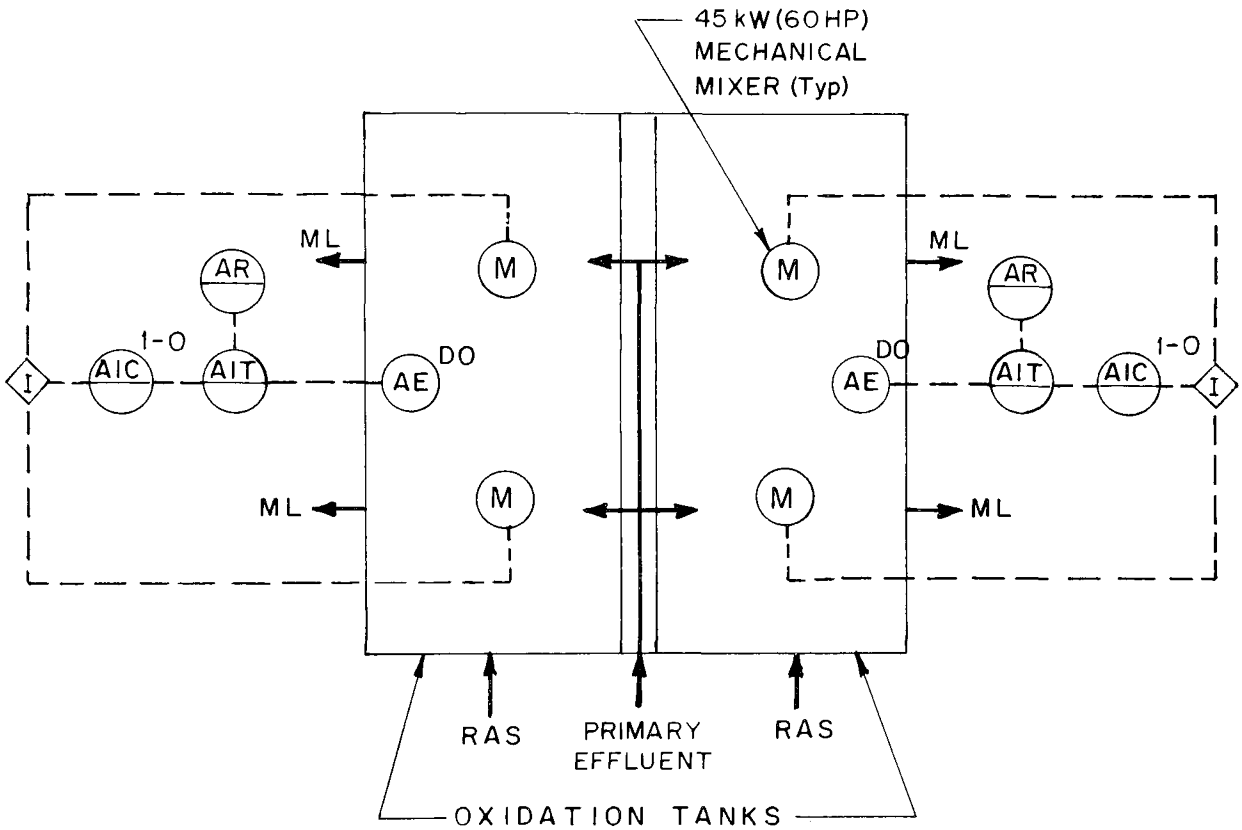


Figure A-12. Automatic dissolved oxygen control system - St. Regis Wastewater Treatment Plant, Sartell, Minnesota.

The DO controller is designed to output a control signal if the DO level deviates beyond a permissible control band. Since the mixers are 2-speed units, the control output causes the mixer to change from one speed to a-another, depending on the oxidation tank DO level.

Performance

From August 10 through August 22, 1975, personnel of the St. Regis Paper Company conducted a performance test for the benefit of this report. Both oxidation tanks were operated in an automatic control mode August 10-17 and August 22 and in a manual control mode August 18-21. Under manual operation, the mixer speeds were varied as required to maintain 1-2 ppm DO in each oxidation tank. The average frequency of mixer speed change adjustment was once every four hours.

Under the automatic control mode, mixer speed was automatically varied to maintain a DO concentration of 1-2 ppm. Test records indicated that the mixer speed was automatically changed about every half hour. One mixer was lost during the test due to bearing failure. Accordingly, data obtained on August 15 and 16 is considered to poorly represent the manual control mode under which the mixers were operating. Certain erratic readings of BOD and suspended solids occurred on other dates that St. Regis Paper Company personnel attributed to boilouts, washouts and sampler line plugging. Thus, selection of suitable time periods for comparison of the manual and automatic DO control modes was difficult due to the testing problems that occurred. August 10-13 and August 18-21 were chosen as the automatic and manual DO control periods, respectively.

The results of the DO control study test are presented in Table A-10 and indicate that automatic DO control provided no significant performance improvement over manual DO control. This result is to be expected since St. Regis Paper Company produces paper 24 hours per day, and the waste stream is, thus, reasonably constant in flow and loading.

Maintenance

According to the St. Regis Paper Company technical assistant responsible for wastewater treatment plant operations, the automatic DO control system has presented no significant maintenance problems since startup in April, 1973. The operating and maintenance staff is generally pleased with the DO control system and offered no complaints.

The DO probes are checked once per week and cleaned and calibrated if required. It is estimated that five man-hours per month is required for DO probe maintenance. Maintenance staff members earn $4.50-4.75/hour. Calibration of probes is performed in the company instrument shop. Calibration time required is estimated as minimal.

TABLE A-10. PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL AT THE ST. REGIS PAPER COMPANY WASTEWATER TREATMENT PLANT[a]

Parameter	Manual[b]	Automatic[c]	Percent improvement
BOD removal efficiency, percent	97	98	1
Suspended solids removal efficiency, percent	88	89	1
Sludge volume index	252	201	20

[a]Data obtained from two four-day test periods conducted August 10-22, 1975.
[b]Average daily flow - 0.246 m^3/s (5.62 mgd). Average BOD loading - 6.45 $mg/m^3/s$ (34.8 lb/1000 cf/day).

[c]Average daily flow - 0.241 m^3/s (5.50 mgd). Average BOD loading - 4.89 $mg/m^3/s$ (26.4 lb/1000 cf/day).
[d]Average BOD loading - 4.89 $mg/m^3/s$ (26.4 lb/1000 cf/day).

The mixers are normally lubricated every three weeks. Lubrication time is estimated at one man-hour per month. The mixer gear drive oil is changed twice per year at a labor requirement of one man-hour per unit or four man-hours total. An additional five man-hours per month is expended in checking the mixers as a preventive maintenance measure. The only significant break-downs to date have been attributed to failure of motor bearings, motor insulation and 460 volt feeder line insulation.

Safety and Emergency Procedures

Power to the waste treatment plant and to the paper processing plant is normally provided by a local utility company. However, on-site steam and hydroelectric power generation equipment permits operation of critical paper company equipment as well as the waste treatment plant during a utility company power failure.

The mixer motors are all equipped with combination starters that contain heaters for overcurrent and fuses for short circuits. Overcurrent or a short circuit will thus cause automatic shutdown of a mixer. All mixers may be started, stopped or have speed changed from a remote control panel. Interlocks are furnished at each motor to prevent remote start when a unit is being serviced.

Spare parts for the mixers and other DO control components are minimal. However, the plant can be operated briefly with one mixer out of service. This situation occurred during the DO control study, resulting in all other mixers being operated at high speed until the fourth mixer was repaired.

CASE HISTORY 10

LONG BEACH WATER RENOVATION PLANT
LONG BEACH, CALIFORNIA

Description of Aeration and Dissolved Oxygen Control System

The Long Beach Water Renovation Plant, located in the southeast portion of Los Angeles County, California, was placed in operation in January, 1973, with a designed capacity of 0.548 m^3/s (12.5 mgd). It is a secondary activated sludge plant with complete nitrification. Flows presently being treated are approximately 0.31 m^3/s (7.0 mgd). One oxidation tank with four passes is provided.

Primary effluent is distributed to the oxidation tank through step feed channels and step feed flow meters. Under current operation, primary effluent is divided equally between the first and second passes through two step feed gates in each pass.

Air is provided by two 10.6 m^3/s (22,500 scfm), single stage, pedestal bearing mounted, centrifugal blowers. Both blowers are supplied with 4160 volt power and driven by 600 kW (800 hp) induction motors. An automatically controlled common bypass system is provided to vent excess air from the common blower discharge line back to suction. For plant odor control, the primary sedimentation tanks, primary effluent channel, and aerator step feed channels are covered. Supply air for the air compressors is withdrawn from under these covers. Air is supplied to the aeration system through coarse bubble diffusers. Air is discharged from the blowers into a common manifold and distributed through two headers to the oxidation tank and through one header to the channel aeration system. Each header is furnished with a flow tube and a control throttling valve. The channel aeration and pass 1-2 header control valve is manually controlled, and the pass 3-4 header control valve is automatically controlled by the DO control system.

Four DO probes are provided with DO probe receptacles located in the middle and effluent end of each pass. Air flow to passes 3 and 4 is throttled by a DO control loop to maintain a desired DO concentration at the selected control probe. Air flow to passes 1 and 2 is indirectly throttled by simultaneously modulating the blower inlet guide vanes and the blower bypass valve through a split range cascade DO control loop to maintain a desired DO concentration at the selected control probe. An instrumentation and control diagram of the DO control system is shown in Figure A-13.

Operation

The process air blowers may be locally or remotely started. However, the plant operators report remote starting is not used because they prefer to observe and listen to each machine during start-up.

Based on the DO output on recorder (AR) and operating experience, the operator selects a DO control probe in pass 3 or pass 4 through selector switch (HS). The output of the probe is transmitted to a DO controller (AIC) that modulates a cylinder operated butterfly valve in the pass 3-4 air feed header to maintain a set point DO concentration in the tank at the DO control probe.

The operator also selects a DO control probe in pass 1 or pass 2 in the same manner as above via a selector switch (HS). The control probe output is transmitted to another dissolved oxygen indicating controller (AIC) that outputs a flow set point to a flow indicating controller (FIC) to maintain the desired tank DO at the control probe. The flow indicating controller (FIC) outputs a 4-20 ma control signal to two relays (FY). One relay accepts any signal between 12-20 ma and modulates the inlet guide vanes of the blowers to deliver the set point flow of the flow indicating controller (FIC). Flow from each blower is metered by flow tubes, transmitted to a summing relay (FY) and input to the flow indicating controller (FIC). The second relay accepts all control signals from the flow controller (FIC) between 4-12 ma and modulates a blower bypass valve to return sufficient discharge air to suction to maintain the blower flow rate above surge condition. Under present operation, the desired DO level is set to be maintained at 1.5 ppm at the middle probe location in the second and fourth passes which are used as the control points.

A problem associated with the above control system observed by the Los Angeles Sanitation District (LACSD) staff with this loop within a loop control scheme is that the DO control loop for passes 3 and 4 may be calling for more air, while the DO control loop for passes 1 and 2 may be calling for less air. Consequently, the throttling valve on the pass 3-4 air feed header may be wide open, and insufficient air may be available for throttling due to DO requirements of the other control loop.

The LACSD only recently implemented the above control scheme as a modification and improvement of the previous DO control system. The District considers it an experiment and is actively seeking alternate DO control configurations to find the best DO control solution for the Long Beach plant.

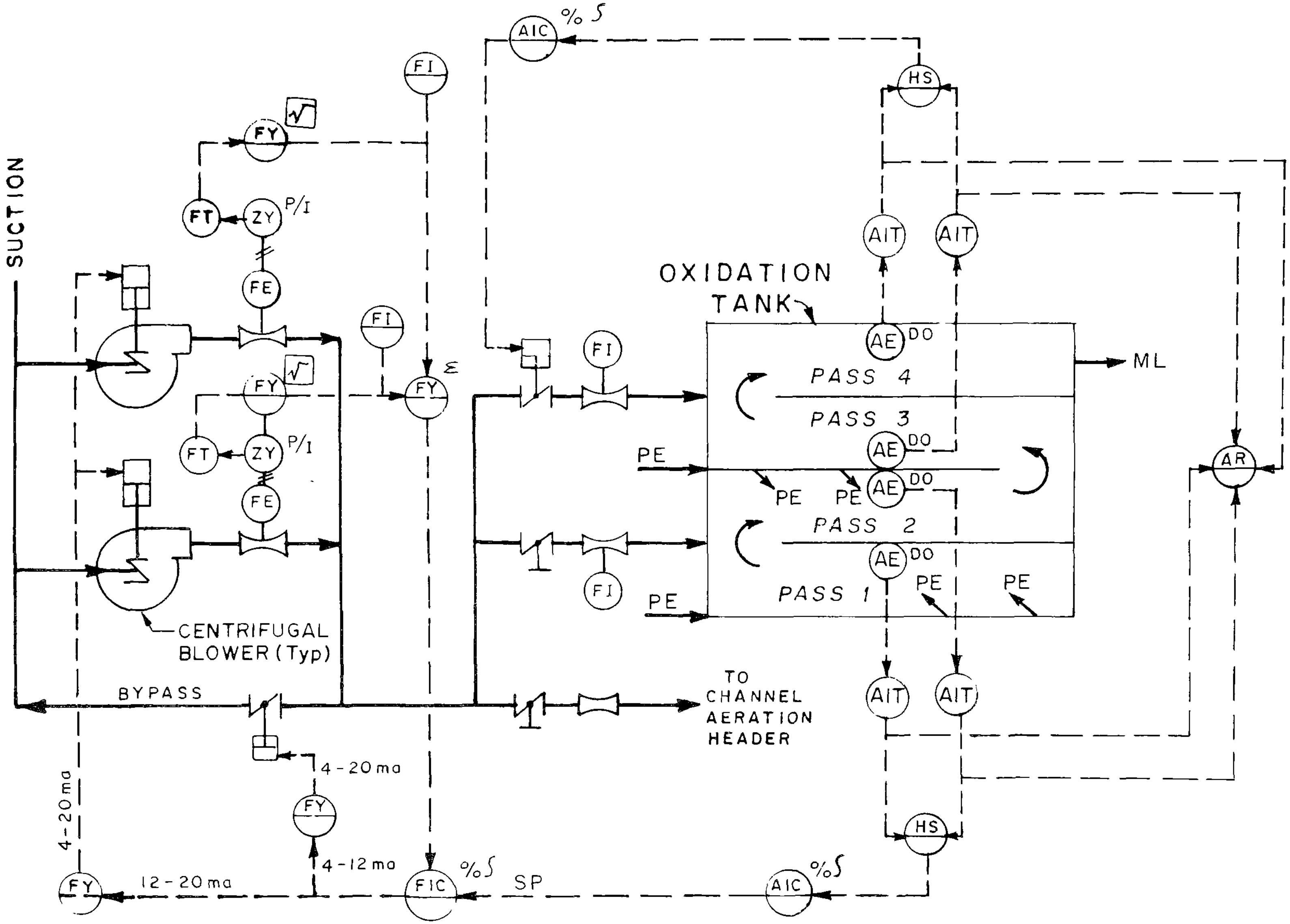


Figure A-13. Automatic dissolved oxygen control system - Long Beach Water Renovation Plant, California.

Performance

For the purposes of this report and an evaluation of the Long Beach Water Renovation Plant DO control system, the LACSD agreed to run a manual vs automatic DO control performance test on August 20-22, 1975. Under manual DO control, air to the third and fourth passes of the oxidation tank was adjusted by manually throttling the header valve. Air to the first and second passes was controlled by manual adjustment of the blower inlet guide vanes. All adjustments were made at approximately one-hour intervals. Under automatic control, the DO control system was operated as described above in the section on operation. A DO concentration of approximately 1.5 ppm was maintained at DO control probes located in the middle of the second and fourth passes for both manual and automatic DO control tests.

As indicated in Table A-11, there was a noticeable improvement under automatic DO control for most of the performance parameters measured. It is expected that improvements would have been greater if manual adjustments of the pass 3-4 butterfly control valve and the blower inlet guide vanes were done less frequently. Adjustments at hourly intervals is considered a fair approximation of automatic DO control.

Maintenance

Maintenance of the DO control system has required minimal labor and material costs. Minor problems have been experienced with DO probe drift. The probes are checked daily by comparing with a portable DO meter. Cleaning and recalibration, if necessary, occurs approximately once per week and requires one man-hour per probe. Recharging and membrane replacement is necessary about once every six to eight months and requires about 4 man-hours per probe.

Maintenance costs of the blowers are also minimal. Typical annual maintenance involves replacing oil filters, conducting vibration analysis for determination of bearing conditions and cleaning of the impellers of volutes. Replacement of oil is conducted only when analysis of the oil indicates dirt or degradation. Since being placed in operation in January of 1972, it has not been necessary to replace the oil or bearings, or make any other type of compressor repair. Annual maintenance labor on the blowers is estimated at approximately 40 man-hours per year per blower.

Safety and Emergency Procedures

The aeration system blowers are monitored and protected by an elaborate instrumentation and control system. Each blower is prevented from operating in a surge condidion by a signal limiting device in the control system which prevents closure of the inlet guide vanes before surge point is reached. In

TABLE A-11. PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL AT THE LONG BEACH WATER RENOVATION PLANT[a]

Parameter	Manual[b]	Automatic[c]	Percent improvement
BOD removal efficiency, percent	97	97	none
COD removal efficiency, percent	90	90	none
Suspended solids removal efficiency, percent	90	90	none
Sludge volume index	99	94	5
Air supplied per unit quantity of influent,			
m^3/m^3	27	25	7
(cf/gal)	(3.6)	(3.4)	
Air supplied per unit quantity of BOD removed,[d]			
m^3/kg	190	180	5
(cf/lb)	(3100)	(3000)	
Air supplied per unit quantity of COD removed,[e]			
m^3/kg	92	85	8
(cf/lb)	(1500)	(1400)	

[a]Data from 24-hour tests on August 20-22, 1975.

[b]Average daily flow - 0.302 m^3/s (6.90 mgd).

Average BOD applied to oxidation tanks - 3.86 $mg/m^3/s$ (20.8 lb/1000 cf/day).

[c]Average daily flow - 0.302 m^3/s (6.90 mgd).

Average BOD applied to oxidation tanks - 3.32 $mg/m^3/s$ (17.9 lb/1000 cf/day).

[d]Computed from total air supplied over testing period and 24-hour composites of primary effluent BOD minus secondary effluent BOD.

[e]Computed from total air supplied over testing period and 24-hour composites of primary effluent total COD minus secondary effluent soluble COD.

case of failure of this system, vibration switches cause blower shutdown if a surge condition occurs. Low oil pressure, high bearing temperature, high oil temperature, and high motor winding temperature are also monitored and cause blower shutdown if normal operating ranges are exceeded.

Under a plant power failure, air flow to the oxidation tanks ceases, and the operating blowers coast to a stop. An auxiliary turbine generator automatically starts and supplies 480 volt power to all other plant processes as well as supplying power to the air compressor lube pumps to supply lubrication while the blowers are coasting to a stop.

CASE HISTORY 11

SAN JOSE-SANTA CLARA WATER POLLUTION CONTROL PLANT, SAN JOSE, CALIFORNIA

Description of Aeration and Dissolved Oxygen Control System

The San Jose-Santa Clara Water Pollution Control Plant began operation in 1964 with an average dry weather flow design of 4.1 m^3/s (94 mgd). In 1973, the plant was expanded to a dry weather flow capacity of 7.01 m^3/s (160 mgd). Currently, the plant is treating an average flow of 3.9 m^3/s (90 mgd). The plant is an activated sludge treatment facility that employs the Kraus Nitrified Sludge Interchange Process. Two tank batteries are provided, each composed of six two-pass oxidation tanks and two two-pass nitrification tanks. However, piping for each battery is arranged to permit conversion of two more oxidation tanks to nitrification tanks if desired. Wastewater may be treated using plug flow, step feed or tapered aeration activated sludge operating modes. Normally, the oxidation and nitrification tanks are operated in the plug flow mode.

The Kraus process utilized involves mixing a portion of the activated sludge with supernatant and digested sludge from the anaerobic digesters and aerating the combination for about 24 hours in the nitrification tanks. The mixture is then pumped to the oxidation tanks for further aeration with the primary effluent.

Two air systems are provided to deliver air to the secondary process at different pressures. The high pressure, or diffused air system, delivers 55 kPa (8 psig) air to twelve oxidation and four nitrification tanks at a level two feet above the tank bottom. Air is introduced from one side of each tank pass through diffusers that produce minute air bubbles. The low pressure, or distributed air system, delivers 28 kPa (4 psig) air to the twelve oxidation tanks at a level five feet below the tank surface. This system introduces air into each tank pass opposite the fine bubble diffusers and produces a much larger bubble diameter.

Six engine driven, single stage, centrifugal blowers supply air for the high and low pressure air systems. Four blowers are furnished for the high pressure and two for the low pressure system. In addition, four additional motor driven rotary, lobe type, positive displacement blowers were installed in 1970 to augment the high pressure air system. These blowers are driven by 298 kW (400 hp) motors and are designed to each deliver 4.7 m^3/s (10,000 cfm) at 55 kPa (8 psig). The diffused or high pressure system engine driven blowers are each designed to deliver 28 m^3/s (60,000 cfm) of air at a pressure of 55 kPa (8 psig) and are driven by 1.8 MW (2400 hp) engines. The distributed, or low pressure system engine driven blowers are each designed to deliver 40 m^3/s (85,000 cfm) at 28 kPa (4 psig) and are driven by 1.4 MW (1850 hp) engines. The engines are tri-fuel units that can operate on (a) a blend of digester gas and natural gas, (b) a blend of digester gas, natural gas and diesel fuel, and (c) diesel fuel.

The low pressure air system blowers are throttled by varying engine speed through a flow control loop that senses blower manifold discharge flow. The high pressure air system blowers are throttled by varying engine speed through a pressure control loop that senses blower manifold discharge pressure. The set point for each 28 kPa (4 psig) and 55 kPa (8 psig) header was manually derived from plant flow (in mid-1975) and experience but will soon optionally originate from a DO or ORP probe located near the second pass end of each tank. The set point for the main 28 kPa (4 psig) header air flow controller is set by operating experience. Each tank header control valve is throttled by a cascade flow control loop to maintain 28 kPa (4 psig) in the low pressure manifold.

During the 1970-73 plant expansion, the plant diffused and distributed air systems were placed under direct digital control using a dual computer system. The previously installed pneumatic control systems remain intact and functional, but the computer was interfaced directly with the primary and final control elements. Control functions previously accomplished by pneumatic analog systems are now effected by either plant computer, utilizing suitable control algorithms analogous to the pneumatic analog control functions. Four nitrification tanks were added to the original twelve tanks during the expansion. The new tanks have all electric instrumentation, thereby eliminating the need for P/I and I/P converters. An instrumentation and control diagram of the DO control system is shown in Figure A-14. Components include the following:

- Single stage centrifugal engine driven blowers with flow regulated surge control system, current transmitter and high and low speed alarms (6 ea.)

- Rotary, lobe type positive displacement, motor driven blowers (4 ea.)

- Low pressure blower discharge flow control system with pitot tube, square root extractor, flow transmitter and flow controller (1 ea.)

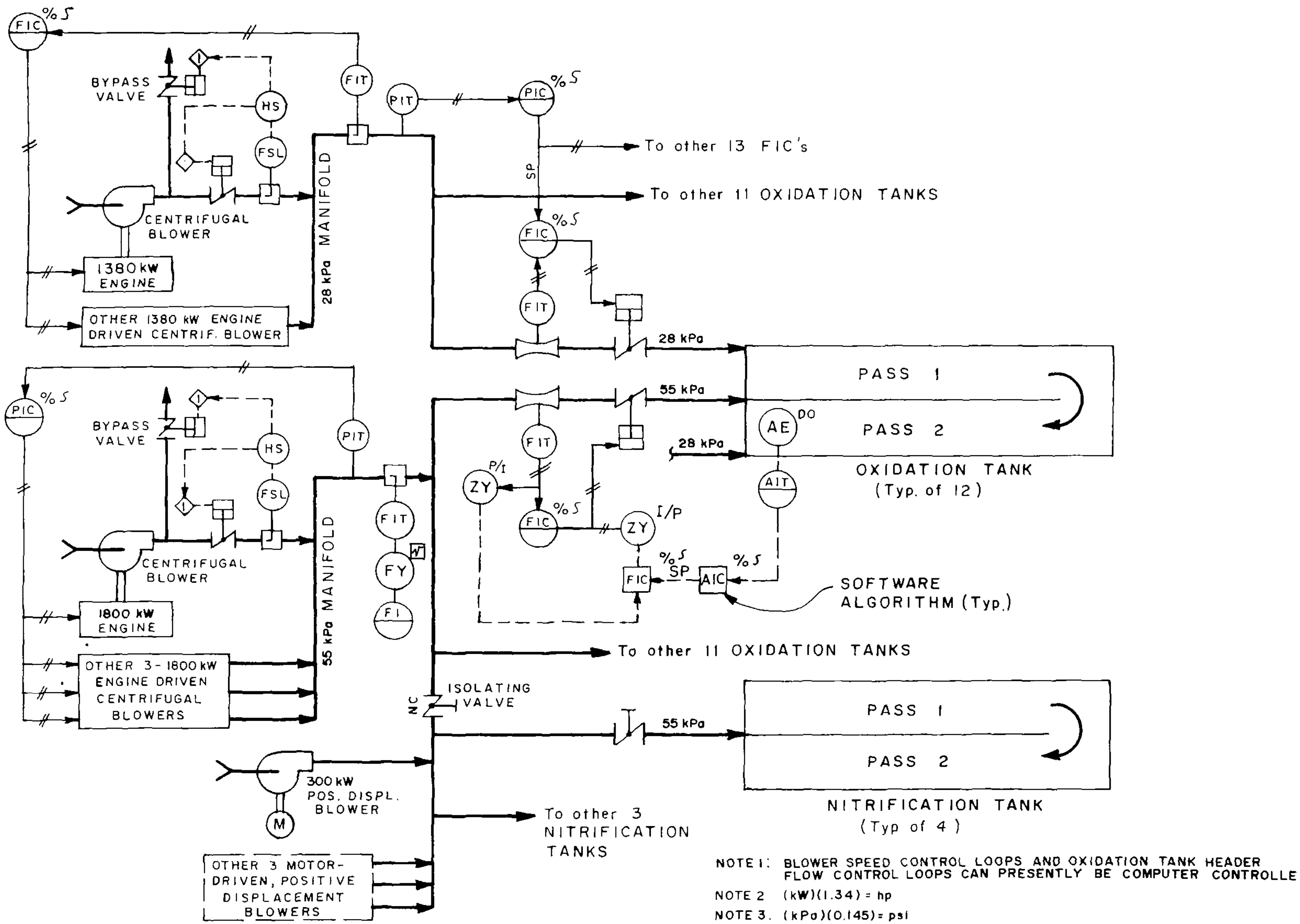


Figure A-14. Automatic dissolved oxygen control system - San Jose/Santa Clara Water Pollution Control Plant, California.

- High pressure blower discharge manifold pressure control system with pressure sensor, pressure transmitter and pressure controller (1 ea.)

- Low pressure header butterfly throttling valves and flow control systems (14 ea.)

- High pressure header butterfly throttling valves and flow control systems (12 ea.)

- Dissolved oxygen probes with analyzer/transmitter (5 ea.) + 5 future

- Oxidation reduction potential probes with analyzer/transmitter (10 future)

- Computers (2 ea.)

Operation

All six blowers at the San Jose-Santa Clara plant are currently computer controlled to deliver a specific flow rate for the low pressure system and a specific pressure for the high pressure system. However, starting and stopping blowers must be done manually from local control panels. The computer receives a linearized flow signal from the FIT connected to the square root extractor (FY) for the pitot tube (FE) in the low pressure discharge manifold. Using a propoportional and integral flow control algorithm, the computer decrements or increments an output signal that controls the fuel supply to the blower engine drives. The high pressure blower speed is controlled in a similar manner with the exception that the computer receives a pressure signal from the PIT connected to a pressure sensor in the high pressure discharge manifold, and a pressure control algorithm is used.

The low pressure or distributed air supply headers are each flow controlled by the computer. The computer receives a signal from the FIT connected to the header flow tube, inputs it to a flow control algorithm with a preset set point and outputs a control signal directly to the butterfly positioner in the header.

The high pressure or diffused air supply to each oxidation tank and nitrification tank is also flow controlled by the computer. Currently, the computer receives a flow input from the FIT in each high pressure air feed header, compares it to a set point using a proportional and integral control algorithm and outputs valve position changes as required to the butterfly valve positioners in each air header.

In mid-1975, the plant installed dissolved oxygen probes in the effluent end of five of the oxidation tanks in one battery. At the computer console, the operator will be able to select DO, plant flow or other variable as a control reference for computer computation of a flow control set point for the flow control algorithm in each high pressure air feed header.

Performance

For the purposes of this study and for a performance analysis of the newly installed dissolved oxygen probes, the San Jose/Santa Clara plant staff agreed to run a DO control study test. A DO probe was installed in the effluent end of four oxidation tanks in Battery B and the DO output wired to the computer. A program called for printout of each DO probe reading at 15-minute intervals. Testing began on October 21, 1975, and ran for a total of eight days. Each oxidation tank was operated under manual DO control October 21, 23, 25 and 27 and under automatic DO control on October 22, 24, 26 and 28.

Under manual DO control, the header air feed valve on the 55 kPa (8 psig) header to each tank was manually modulated approximately every four hours. The amount of valve position change required was estimated based on the computer printout of DO in the respective tank.

Under automatic DO control, the computer modulated the air header feed valves as required to maintain a DO set point of 2.5 ppm in each tank. The control algorithm included proportional and integral control modes.

Blower control systems under manual and automatic DO control were operated as described above in the section on performance. DO in each tank was maintained at approximately 2.5 ppm throughout the testing program. Results of the performance tests are shown in Table A-12.

Table A-12 shows a general improvement in almost all performance parameters under automatic DO control. In particular, the air supplied per unit quantity of BOD removed improved over 12 percent. Improvement of this parameter would have been about 16 percent if data obtained on October 26 is neglected. For some unexplained reason, the air supplied per amount of BOD removed was about 28 percent higher in this day than any other day on automatic DO control mode.

Maintenance

Since the DO control system was only recently installed, maintenance data is not available.

TABLE A-12. PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL AT THE SAN JOSE/SANTA CLARA WATER POLLUTION CONTROL PLANT[a]

Parameter	Manual[b]	Automatic[c]	Percent improvement
BOD removal efficiency, percent	85	85	none
Suspended solids removal efficiency, percent	86	86	none
Sludge volume index	102	101	1
Air supplied per unit quantity of influent,			
m^3/m^3	6.7	6.0	10
(cf/gal)	(0.89)	(0.80)	
Air supplied per unit quantity of BOD removed,[d]			
m^3/kg	37	33	11
(cf/lb)	(600)	(520)	

[a] Data from continuous tests on October 21-28, 1975; automatic control on alternate days.

[b] Average daily flow - 1.97 m^3/s (45.0 mgd).

Average BOD applied to oxidation tanks - 10.1 mg/m^3/s (54.3 lb/1000 cf/day).

[c] Average daily flow - 2.01 m^3/s (45.9 mgd).

Average BOD applied to oxidation tanks - 10.4 mg/m^3/s (56.1 lb/1000 cf/day).

[d] Computed from total air supplied over testing period and 24-hour composites of primary effluent BOD minus secondary effluent BOD.

CASE HISTORY 12

CRANSTON WATER POLLUTION CONTROL FACILITY, CRANSTON, RHODE ISLAND

Description of Aeration System

The City of Cranston Water Pollution Control Facility was built in 1942 with an average dry weather flow design of 0.20 m^3/s (5 mgd). During 1964, it was expanded to its present average flow capacity of 0.50 m^3/s (11.4 mgd). The plant is an activated sludge facility using the contact stabilization process. Aeration facilities include four oxidation and four contact stabilization tanks. However, one oxidation tank and associated contact tank is not currently being used. Return sludge can be applied directly to each oxidation tank inlet, or first to the contact stabilization tank and then to the oxidation tank at any desired ratio. Presently, the plant operates with a 30 percent direct return and 70 percent diversion to contact stabilization.

The aeration system for the plant expansion (tanks 3 and 4 and associated contact tanks 3 and 4) is made up of two independent parts called the upper and lower aeration systems. Aeration air is provided by lobe type, rotary, positive displacement blowers, driven by 220 kW (300 hp) wound rotor motors. Each blower may be remotely controlled to operate at 1/2, 3/4 or full speed.

Upper aeration air is delivered to all oxidation and contact stabilization tanks through a single manifold and applied to each tank via a separate feed header. It is introduced through diffusers at a high level in the tank at about 34 kPa (5 psi).

Lower aeration air is provided to oxidation tanks 1 and 2 and contact tanks 1 and 2 by the old blower system and to oxidation tanks 3 and 4 and contact tanks 3 and 4 by the new blower system. Delivery pressure is approximately 48 kPa (7 psi). Lower aeration air is introduced to each new oxidation tank and associated contact tank by a single header.

Description and Operation of the Dissolved Oxygen Control System

In late 1975, a demonstration project was underway at the plant in which the Environmental System group of the Raytheon Company intended to show the economic benefits and improvements in plant operation realized by microcomputer control of the activated sludge process. DO control will be an integral part of the overall process control system. Four DO probes have been located in oxidation tank 3.

Since the micro processer and other control components are not presently installed, an automatic DO control system, as illustrated in Figure A-15, was temporarily arranged for the purpose of this study. In Figure A-15, air flow to oxidation tank 3 is modulated by throttling a motor operated butterfly valve in the air feed header to tank 4 through analog flow controller (FIC). The FIC set point is provided by DO controller (AIC), which receives a process input from the DO probe (AE) located ten feet from the tank effluent weir. At a given blower speed, a constant amount of air is discharged from the positive displacement blower. By varying the resistance in the air feed header to tank 4 through the butterfly valve, more or less air is diverted to tank 3.

Performance

For this study, the Cranston plant staff and personnel from Raytheon agreed to perform 24-hour DO control tests. One manual and two automatic DO control tests were run during the period November 20-26, 1975.

Under manual DO control, air flow to basin 3 was adjusted every four hours to maintain 1 ppm of DO. Under automatic DO control, the set point on the AIC was set at 1 ppm and the control system was operated as described above. Test procedures were performed as described in the first part of Section VII of this manual. Manual DO control was effected by manually setting the FIC set point every four hours rather than having it set by the AIC. Blower speed in both tests was manually varied in accordance with the system requirements.

During the first automatic DO control test, a thunderstorm caused a one-hour power outage. Accordingly, the automatic test was rerun. Table A-13 shows results of all three DO control tests.

In general, automatic DO control provided an increase in BOD removal and a decrease in air supplied. Results for suspended solids removal are inconclusive since removal increased in the first automatic test and decreased in the second automatic test.

SVI data reported in Table A-13 is an average of six samples taken during each test. SVI's at the plant generally run about 50. A graph of SVI data shows 70 percent of all samples fell within a range of 40-60. The remaining samples were all higher than 60 with several samples during the automatic tests being above 100. Insufficient data exists to draw any conclusions with regard to SVI readings and DO control.

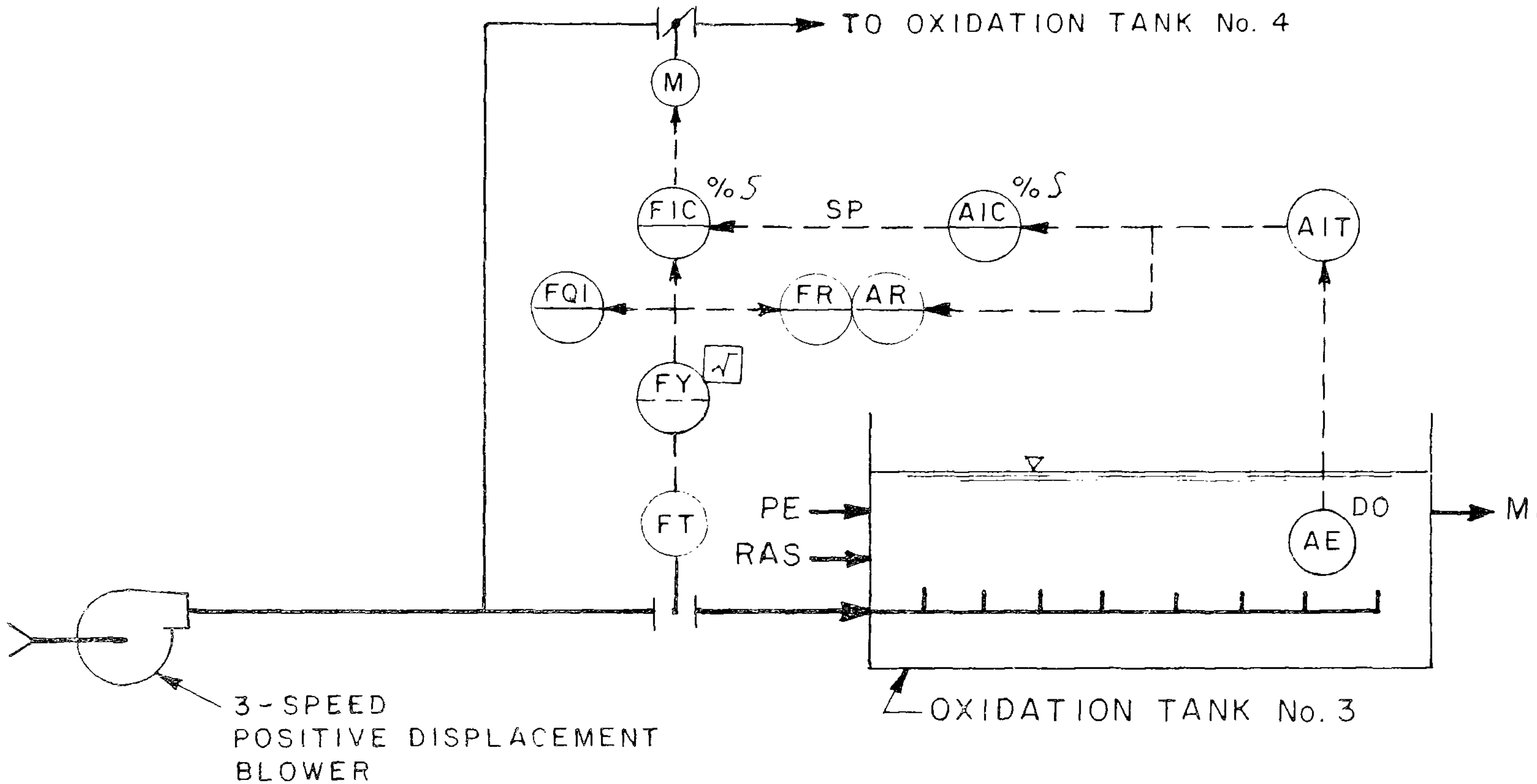


Figure A-15. Automatic dissolved oxygen control system - Cranston Water Pollution Control Facility, Rhode Island.

TABLE A-13. PERFORMANCE COMPARISON OF MANUAL AND AUTOMATIC DISSOLVED OXYGEN CONTROL AT THE CRANSTON WATER POLLUTION CONTROL FACILITY[a]

Parameter	Manual[b]	Automatic[c] # 1	Percent improvement	Automatic[d] #2	Percent improvement
BOD removal efficiency, percent	91	94	3	92	1
Suspended solids removal efficiency, percent	89	96	7	83	-6
Sludge Volume Index	56	60	-7	69	-23
Air supplied per unit quantity of influent, m^3/m^3 (cf/gal)	19 (2.5)	15 (2.0)	21	16 (2.2)	16
Air supplied per unit quantity of BOD removed, m^3/k_s (cf/lb)	79 (1300)	58 (940)	27	56 (900)	29

[a] Data from 24 hour tests November 20-26, 1975.

[b] Average flow to oxidation tank 3 - 0.16 m^3/s (3.60 mgd).
Average BOD applied to total volume of oxidation tank 3 & contact tank 3 9.08 $mg/m^3/s$ (49.0 lb/1000 cf/day).

[c] Average flow to oxidation tank 3 0.20 m^3/s (4.59 mgd).
Average BOD applied to total volume of oxidation tank 3 & contact tank 3 - 12.2 $mg/m^3/s$ (65.6 lb/1000 cf/day).

[d] Average flow to oxidation tank 3 0.19 m^3/s (4.23 mgd).
Average BOD applied to total volume of oxidation tank 3 & contact tank 3 13.2 $mg/m^3/s$ (71.3 lb/1000 cf/day).

Maintenance

Since installation in August, 1975, until the DO control testing period described above, DO probe maintenance has consisted of one cleaning and one membrane replacement for each probe. DO probe readings have been found to consistently agree well with DO analysis by the Winkler method.

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[a]Much of the information contained in the Appendix was obtained through private communications between Brown and Caldwell staff members and responsible operating and management personnel at the various plants. Other information was extracted from Brown and Caldwell job files.

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16. ABSTRACT

This report presents design procedures and guidelines for the selection of aeration equipment and dissolved (DO) control systems for activated sludge treatment plants. A review of process configurations and design parameters is made to establish system requirements. Aeration methods, equipment and application techniques are examined and selection procedures offered. Various DO control systems are described with recommendations for system applications to various aeration equipment types and process configurations. Performance, operational and maintenance data for aeration equipment and DO control systems for twelve activated sludge plants is presented. This information and other design recommendations in the report are used to develop automatic DO control systems for various size hypothetical activated sludge system configurations for an economic analysis of manual and automatic DO control. The conclusion is drawn that the capital and operating costs of automatic DO control systems are justified for activated sludge plants larger than 1 mgd (44 dm^3/s) provided equipment is selected and applied in accordance with the guidelines of the design manual and a power cost equal to or greater than the national average power rate is applicable.

17. KEY WORDS AND DOCUMENT ANALYSIS

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